Dimethyl ether fuel literature review
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Dimethyl Ether Fuel Literature Review

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DIMETHYL ETHER FUEL LITERATURE REVIEW

Image taken from www.volvotrucks.com

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Technical Report

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ABSTRACT

Dimethyl Ether (DME) is gaining acceptance as an alternative fuel for compression ignition engines in Asia and Europe. DME is also being marketed in North America therefore Transport Canada wished to better understand the properties, emissions, and operational considerations of the fuel use in heavy duty vehicles. The physical and chemical properties of DME were studied as well as any tailpipe emissions, costs and what steps are required to convert an existing vehicle to operate on DME. Comparisons were drawn between DME and diesel as we well as other alternatives fuels such as propane and natural gas. Finally, safety and environmental issues were studied. The results of this literature review are presented in this document.

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EXECUTIVE SUMMARY

Transport Canada (TC), through its ecoTECHNOLOGY for Vehicles (eTV) program, has retained the services of the National Research Council Canada (NRC) to undertake a comprehensive literature search to study the production, distribution, handling and use of Dimethyl Ether (DME) in road vehicles as a substitute for conventional pump diesel. Although DME can theoretically be used to power vehicles in any sector (e.g. passenger vehicles, off-road equipment) the principal thrust of this study involves diesel engines that have been modified, or designed, to accept DME and used in the heavy duty on-road sector. The main purpose will be to present the attributes of DME as they pertain to heavy duty vehicles but also to present any limitations the fuel may have for use in Canada.

NRC-AST used the services of NRC's Knowledge Management (KM) group to retrieve as many DME related journals, papers, presentations, test results and dissertations from academics as well as marketing and specification documents from the commercial trucking sector. Although much of the information was retrieved from academic papers from all over the world, care was taken to not focus entirely on the chemical theories of DME. Rather, the theory was blended with the industry-specific requirements that were pertinent to the heavy haul sector in Canada to form a study that can be used to fully understand how DME can be used in Canada. More importantly, any of the limitations that must be understood by operators, drivers, refuellers, government regulators and the motoring public have also been explored. In all, over 70 papers, presentations and industry documents formed the basis of the references for this research study.

Dimethyl Ether (DME) is an organic compound with the chemical formula CH_3OCH_3. For decades it has been used in a variety of products and applications such as propellants in aerosol cans, cooking fuels, solvents and medical treatments due to its lack of odour and toxicity and its ability to be absorbed into the troposphere. However, it can also be made into a viable alternative for diesel fuel, most notably for use in heavy haul transport vehicles.

Unlike conventional diesel which is produced from non-renewable crude oil, DME can be produced anywhere using renewable products like natural gas, crude oil, propane, residual oil, pulp and paper waste, agricultural by-products, municipal waste, fuel crops such as switchgrass, coal, and biomass such as forest products and animal waste. This provides a great deal of flexibility for production since facilities do not need to be located near sources of crude oil but can be setup any place where bio based feedstocks or natural gas can be found, or produced.

The current estimated yearly production of DME is approximately 5 million to 9 million tons, depending on the cited source. The literature review revealed many methods by which DME may be produced. In general though, DME is currently produced via the dehydrogenation reaction of methanol. Based on current projections, it is likely that the abundance of North American natural gas and a high level of animal waste could provide ample sources for future DME production without reliance on offshore resources. It takes approximately 1.4 tons of Methanol to produce approximately 1.0 ton of DME. Other forms of production such as the use of pulp and paper process waste such as black liquor were also identified. A joint venture between Volvo and Chemrec in the North of Sweden produced 4.3 tons of black liquor based DME per day to power a dedicated fleet of four tractor-trailers.

Oberon Fuels manufactures skid mounted small scale DME production units meant to replace large scale infrastructure projects that could cost hundreds of thousands of dollars. The units can produce between 3,000 and 10,000 gallons of DME a day (11,340 litres to 37,800 litres.

This process is ideally suited to regional haulers with large fleets who see each of their vehicles daily and want to reduce costs by not only self fueling, but self-producing the fuel.

DME exists as an invisible gaseous ether compound under atmospheric conditions (0.1 MPa and 298 K) but must be condensed to the liquid phase by pressurization above its vapour pressure at about 0.5 MPa (5.1 bar/73 psi) at 25 °C to be used as a diesel fuel alternative. One of the more significant features of DME is the lack of a direct carbon-to-carbon bond that is found in traditional diesel fuels. Conventional diesel contains no oxygen whereas DME is an oxygenated fuel and contains about 34.8% oxygen by mass with no carbon-to-carbon bonds. The increase in oxygen content can reduce the precursors to soot formation like C_2H_2, C_2H_4 and C_3H_3. The presence of oxygen can also reduce auto ignition since the C-O bond energy is lower than the C-H bond energy found in conventional diesel. DME has approximately 66% of the energy content, by mass, and about 50%, by volume, of diesel fuel.

The air/fuel ratio of DME fuel at stoichiometric conditions is approximately 9 versus 14.6 for diesel meaning that complete combustion of 1 kg DME requires less air than that of 1 kg diesel fuel. However, more than 1 kg of DME is required to provide the same amount of energy as 1 kg of diesel. DME has a much higher, and wider, flammability range (i.e. the volume of fuel, expressed as a percentage in an air mixture at standard conditions, where ignition may occur) in air than the three hydrocarbon fuels (gasoline, diesel and propane but very similar to natural gas. DME is sulfur free whereas even ultra-low sulfur diesel (ULSD) contains some sulfur.

Most #1 and #2 pump diesel fuels have cetane numbers between 40 and 45 and many bio-diesels have CN greater than 50. DME has a cetane number between 55 and 60, which makes it very suitable for a diesel cycle engine. This reduces engine knocking and engine noise when compared to engines powered with conventional diesel and also helps to provide a more complete combustion process with less wasted fuel, particularly at engine start up or when in-cylinder temperatures cool off. Fuels such as propane and natural gas have high octane numbers but cetane numbers less than 10, making them impractical for dedicated use in a diesel cycle engine unless they are combined with at least some diesel as an ignition source.

DME in the liquid state has low viscosity and low lubricity, two properties which strongly affect the maximum achievable injection pressure in a fuel injection system: viscosity allowing it to readily pass through narrow passages and the lack of lubricity can accelerate the wear of surfaces moving relative to each other such as the feed pump, the high pressure injection pump, and injector nozzles. Due to the low viscosity and lubrication characteristics, fuel additives are mandatory to improve the fuel viscosity to make DME a viable fuel for on road engines.

In addition to its low lubricity and viscosity, DME adversely affects many types of plastics and rubbers and also dissolves nearly all known elastomers found in the fuel system. Retrofitting a vehicle to burn DME that is equipped with elastomers and certain plastics could result in very short service life of those components and possible fuel leaks or a reduction in working pressure. Laboratory tests have demonstrated that DME is compatible with Teflon® and Buna-N rubber. Tests have demonstrated that the bulk modulus of DME is approximately 1/3 that of conventional diesel. Research has demonstrated that due to DME's low elastic modulus, the compressibility of DME is higher than that of diesel fuel, which means that the compression energy in the DME fuel pump is greater than that in the diesel fuel pump. The differences between diesel and DME with regards to lubricity, viscosity, bulk modulus and energy density means that many components in the fuel system must be changed when converting from diesel to DME. The fuel injection timing and duration must also be altered.

Some laboratory tests using pure DME instead of diesel have caused pump failure in less than 30 minutes. Adding a small amount of lubrication significantly increased lubricity but still not to the point where it could be considered acceptable for the typical expected life of a highway tractor. They concluded that raising the lubricity of DME to acceptable levels may not be possible but changing the designs of the pumps to accept pure DME could be a much more viable option. Some researchers have concluded that one of the more significant challenges in using DME as a diesel-fuel substitute is the modification, tuning and management of the engine fuel delivery system.

Particulate Matter (PM), or soot formation, in a DME-fueled engine is almost zero because DME has an oxygen content of 35% and no carbon-to-carbon bonds. Many tests and research programs have demonstrated that DME powered vehicles have PM levels that are orders of magnitude less than diesel PM levels and can pass all current worldwide emissions regulations without the use of any type of diesel particulate filter or trap. Studies have shown that as much as 99% of the PM released from a DME engine is in the nano particle size, which can cause more damage to human health than the larger particle sizes. However, it is not clear from the research if the absolute volume and count of PM particles could pose a risk to human health as a result of tailpipe emissions from Canadian vehicles given that this could be 99% of what is already a miniscule value.

The relationship between NO_x formation, the use of selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) is less clear than the formation of particulate matter. The near zero levels of PM means that PM burn off in the engine is not required thus in cylinder temperatures can be lowered, which reduces the levels of NOx. Some tests have demonstrated that DME powered vehicles can be operated without the use of SCR for NOx reduction with the addition of light EGR to reduce NOx levels and diesel oxidation catalysts to reduce carbon monoxide and hydrocarbon levels to below emissions regulation levels. However, most of these tests were conducted when emissions regulations were slightly less stringent than today. More testing will be required to determine if a DME powered vehicle can pass current emissions regulations for PM, NOx, CO and HC without the use of SCR and what level of EGR and catalysing would be required to compensate for this lack of SCR. Additionally, it will be important to maintain a level of EGR that does not increase fuel consumption or contribute to engine wear. The primary benefits of removing SCR from vehicles are as follows: reducing cost, reducing weight, reducing the need to replenish a consumable fluid and removing a piece of equipment that can cause an engine derate when a fault occurs, be it actual or nuisance.

Research has shown that HC and CO emissions from a DME-fueled engine are usually lower than or equal to that of a diesel engine. However, if SCR is removed and EGR is used to cool the in cylinder temperature it will result in higher levels of CO and HC which can then require the use of a diesel oxidation catalyst to reduce CO and HC levels. Additionally, if high levels of engine injection advance are requested (more than 20 degrees) it can result in levels of CO and HC that are significantly higher than what is currently allowed in North America for on-road and off-road vehicles. Therefore, careful consideration must be given to the inter relationship between engine timing and EGR levels otherwise the reductions of PM may be offset by increase in other pollutants.

DME produces less exhaust, by mass, than diesel and less CO_2 than diesel. DME produces more water than diesel but not orders of magnitude more (as is the case with fuel cells) therefore it is assumed that the incremental effect to cold road surfaces would be minimal, when compared to diesel. For every 43 MJ of fuel energy, DME produces approximately 0.70 kg less total exhaust, 0.30 kg less CO_2, and 0.55 kg more H_2O than diesel fuel. This may not be a large reduction in CO_2 but it does mean that an engine that is slightly above the maximum allowable levels for CO_2 under Canada's new GHG reduction strategy could potentially pass the regulations if fueled with DME, assuming horsepower and fuel consumption remained the same.

The Carbonyl compounds such as formaldehyde (HCHO), acetaldehyde (CH_3CHO), and formic acid (HCOOH) have all been found to be higher for DME than for diesel. This is due to the high Oxygen content and additives in DME whereas diesel is Oxygen-free. Formaldehyde can be reduced to negligible levels by the use of a diesel oxidation catalyst whereas catalysts have no effect on the reduction of acetaldehyde. Careful attention will need to be paid to the lubricity additives that are mixed with DME as they can adversely affect the generation of these Oxygen based compounds and the reduction in PM could be offset by an increase in other toxins.

It is clear that any DME powered vehicle can pass any emission standard in the world (at the time of report preparation) for PM without the use of a particulate filter or trap.

DME's energy density (1.88 DGE) on a volumetric basis is lower than that of LNG (1.56 DGE) but higher than that of CNG (3.98 DGE). Other alternative fuels such as CNG, LNG and LPG are all used in spark ignition engines and therefore require special maintenance such as spark plug replacement. DME powered engines can be maintained similarly to diesel engines with more attention being paid to fuel lubricity to prevent premature failure of pumping and fuel injection components.

DME is stored at pressures that are higher than diesel, but similar to LPG and much lower than CNG.

CNG and LNG fuel tanks are significantly heavier and more expensive than DME fuel tanks. Some papers indicate that LNG and DME tanks can be more than 350 kg heavier than similarly sized DME tanks. Exact figures were difficult to obtain but the size and weight of DME fuel tanks should only be marginally higher than diesel fuel tanks, however, range will be reduced due to the lower energy content of DME.

Because DME has approximately only two thirds of the energy content of diesel by mass, and 50% by volume and only 80% of the physical density, the fuel consumption data must be multiplied by the diesel gallon equivalency (DGE). Typical DME raw test results are between 2.5 mpg and 3.0 mpg at cruising speed. However, when DGEs are considered, the values correspond to fuel consumption rates of over 5.00 mpg which is consistent with current heavy duty tractor fuel consumption values.

DME can be stored for long periods of time in outdoor storage tanks that are exposed to direct solar radiation without any boil off or venting.

As a minimum, DME powered vehicles will require a new fuel tank, new fuel lines, new fuel pumps and injectors as well as new/improved seals and gaskets and modified engine management mapping and software to control the timing of the fuel injections. The addition of a larger and heavier pressure vessel fuel tank (similar to LPG) and some form of EGR could possibly be offset by the removal of the diesel particulate filter and possibly the SCR componentry. Whereas LNG and CNG vehicles must carry very heavy pressure vessel tanks that can reduce payload capacity, the net effect on weight to a heavy duty vehicle powered by DME should be negligible when compared to current diesel powered vehicles. If SCR can be removed there will likely be a small weight savings for DME. However, the range of the vehicles will be reduced to approximately 50% of current distances, which could necessitate a much larger tank which would then increase the weight to current diesel truck levels.

Many other minor vehicle modifications must be implemented such as pressure relief valves, non sparking metal components such as brass, shields and valve covers etc. However, none of these components will add enough weight to seriously affect the payload capacity of a load carrying vehicle.

Unlike most LNG/CNG/LPG engines that require spark plug replacement at specified intervals, DME engines can be serviced in a similar fashion as other compression ignition engines. Despite the fact that many components on DME engines must be changed from conventional diesel engines, they are still the same type of components so the maintenance philosophy can remain.

The low lubricity of DME could necessitate, at least in the near term, an increase in fuel component inspections and or replacement. More data will be required to determine the long term effects on the reliability of all fuel wetted components for long haul operations where fuel pump failure far away from the maintenance base would be considered a highly undesirable situation.

Approximately 7% less air, and presumably 7% less dirt and contaminants, will be drawn into a DME engine compared to diesel engines. It is not likely that air cleaner/filter intervals will need to be modified based on this relatively small change in air flow. Nonetheless, DME engines should be slightly cleaner than diesel engines under identical situations.

Diesel engines currently require oils that are specifically formulated to manage the soot that is generated inside the combustion chamber. More study will be required to determine if the lack of soot in DME powered engines could, or should, result in the use of a different grade of oil, perhaps more similar to those used in gasoline engines.

Vapour fuel leaks under the hood can cause engine over-speeding as raw fuel is ingested into the air intake system.

More study would be required to better understand how DME would affect the mean time between failure of any fuel wetted component, including the fuel system and the engine itself.

In general, DME behaves like propane/LPG and can be handled as such. As with LPG, DME is heavier than air and can pool on the floors of underground garages thus preventing an explosion hazard if a source of ignition were to be dropped into the pool.

Fire fighters will be required to receive training on the ways to extinguish a DME fed fire since improper technique can lead to explosions. DME is considered a dangerous good in the hazard class 2.1 and must be transported in a vehicle with a placard mounted that contains the necessary information.

The MSDS sheets for DME indicate that personnel who handle the product should wear gloves and eye protection as well foot protection. The level of protection is similar to personnel who are dispensing LPG and CNG and slightly less than those dispensing LNG.

From the driver’s perspective there is very little to be concerned with outside of the need to fully understand how to fill the DME tank and understanding any range limitations that may differ from their diesel powered vehicles so that they are not stranded in inclement weather. The vehicle will look and feel the same and will likely be slightly quieter with less knocking at start up when compared to diesel.

Very little data could be found related to the performance of DME in cold weather climates such as Canada. The joint Volvo and Chemrec DME project was a two year project that operated continuously throughout all of Sweden’s four seasons, including their cold winter months. Some of the operations were conducted as far north as the 65th parallel which runs through all three Canadian territories. The test team did not report any operational issues related to ice, snow or cold temperatures. It is not known if Sweden uses salt on their roads to the same extent that is used in some Canadian provinces. Some specific recommendations for cold weather operations were found involving the use of corrosion resistant tanks and fasteners to minimize the risks of salt induced corrosion perforation. However, these recommendations are likely already 'best practices' for diesel vehicles. Rigorous yearly inspections may be required to ensure that fuel tank integrity has not been compromised due to corrosion. DME tanks are pressure vessels and are therefore more rugged than conventional diesel tanks thus the risk of tank failure is actually lower. However, the consequences of a tank failure are potentially more severe since it is a pressurized gas that could be expelled at high velocity whereas diesel fuel remains, at all times, in the liquid unpressurized phase.

At the time of report preparation there were no known DME fuel stations in Canada. This is in contrast to the approximately 100 public and private LNG and CNG stations found across Canada and the abundance of diesel fuel stations. This lack of publicly available DME means that the use of DME in heavy vehicles will likely have to be staged if is to be accepted by the industry. The first phase of DME use would most certainly be for use in fleets that return back to their base every evening for refuelling, be they public or private. These could include urban transit buses, waste collection vehicles, vocational vehicles such as concrete mixers etc. The current lack of infrastructure would make it nearly impossible for long haul tractor trailer operations or for intercity motor coach buses. The reduced range of DME vehicles combined with the fact that, once converted, DME vehicles can no longer operate on any other fuel will dictate that a significant DME network must be constructed along major corridors to support fleet operators who choose to commit to using DME.

The consumer cost of a litre of DME is extremely difficult to quantify at this time. The International DME Association states that the consumer cost of DME is roughly 75% to 90% that of LPG. They also noted that pure LPG prices fluctuate more since LPG is a petroleum based fuel and must follow global petroleum pricing. Oberon, the largest producer of DME in the United States simply states that DME is "competitive with diesel prices" but does not list a consumer cost on their website

Until more accurate data are available, it is fair to assume that the cost per km of delivered DME, on a diesel gallon equivalency, is approximately the same as diesel fuel. The cost per litre may be lower, but since more DME must be burned per distance driven, the cost per km of the fuel should be similar. However, it must be restated that not enough data were available to perform such a calculation with any certainty.

More study may be required to determine the quantity and effects of the nano PM particles that are being created by a DME powered engine, not only in terms of human health but in terms of engine wear;

Engine oil and engine wear analysis could be performed to determine the long term effects of using diesel engine oil, gasoline engine oil or combinations of these to understand the full effects of engine wear by DME;

The levels of carbonyl compounds were difficult to quantify therefore further work in this area may be warranted in order to fully quantify these emissions and their potential to affect human health and infrastructure;

A computational fluid dynamics study could be undertaken to determine how DME pools and accumulates in enclosed and confined spaces such as parking garages. This will be important information to have for property owners and vehicle maintenance shop owners who need to mitigate the risks of possible leaks on their properties;

A full well to wheel analysis of a few of the production methods of DME would be useful in determining how DME compares to, say, biodiesel in terms of emissions and production costs;

A full economic analysis could be performed using CNG, LNG, LPG, DME and conventional diesel to quantify the cost of fuel, consumables and maintenance to operate a long haul tractor for its entire life cycle. It is likely that this has already been performed for the non DME fuels therefore the addition of DME would provide a useful comparison as no such study for those who are considering using the fuel;

One of the greatest potential benefits to operators is the possible removal of the SCR system. A project could be undertaken to test a vehicle with variable EGR and no SCR to determine if a DME powered vehicle could pass the current set of EC emissions standards without SCR, without any increase in fuel consumption. A second set of tests with SCR would be required to compare the results.

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1 INTRODUCTION

1.1 Purpose

Transport Canada (TC), through its ecoTECHNOLOGY for Vehicles (eTV) program, has retained the services of the National Research Council Canada (NRC), as represented by the portfolio for Automotive and Surface Transportation (AST), hereafter known as NRC-AST, to undertake a comprehensive literature search to study the production, distribution, handling and use of Dimethyl Ether (DME) in road vehicles as a substitute for conventional pump diesel. Although DME can theoretically be used to power vehicles in any sector (e.g. passenger vehicles, off-road equipment) the principal thrust of this study involves diesel engines that have been modified, or designed, to accept DME and used in the heavy duty on-road sector. The main purpose will be to present the attributes of DME as they pertain to heavy duty vehicles but also to present any limitations the fuel may have for use in Canada.

1.2 Background

It is currently very challenging for alternative propulsion systems to compete with the features of a modern 'clean diesel' engine combined with today's ultra-low sulfur diesel (ULSD) fuel. The combination provides high energy density with simple and efficient transport and storage and significantly reduced tailpipe emissions compared to previous diesel engines. [1] Many alternative fuels do provide lowered tailpipe emissions when compared to clean diesel, however, the sparse distribution network and shorter vehicle range, compared to that of conventional diesel, makes it more difficult for long haul operators to commit to alternative fuels at this time.

Dimethyl Ether (DME) is an organic compound with the chemical formula CH_3OCH_3. For decades it has been used in a variety of products and applications such as propellants in aerosol cans, solvents and medical treatments due to its lack of odour and toxicity and its ability to be absorbed into the troposphere. [2] DME is also used as a cooking fuel in parts of Asia. DME, as a propellant, is sold by Dupont Corp. as 'Dymel A'.

However, it can also be made into a viable alternative for diesel fuel, most notably for use in heavy haul transport vehicles. For example, The Volvo Group has identified DME as one of the most promising alternative fuels [1]. Volvo announced on June 6, 2013 that they would start commercial production of DME fueled engines for at least some of their heavy duty trucks destined for the US market but their originally scheduled delivery date of model year 2015 vehicles has been delayed in order to perform more field testing. [1] [3] [4] [5] The literature review revealed that although major vehicle manufacturers are only recently developing engines to accept DME conversions, the concept of using DME for on-road vehicles dates back to at least the early 1990s.

1.3 Objectives

The primary objective of this DME fuel study is to present all of the properties and potential uses of DME in terms of its applicability as a fuel to be burned in heavy truck diesel engines. More importantly, however, focus will be placed on presenting all of the possible secondary effects that the fuel could have on the industry, the engines, the operators and to the motoring public. Although the chemical attributes of DME will be discussed in detail, the main intent is to present a system level and heavy-truck sector (class 7 and 8) specific review of the use of the fuel rather than a scientific paper on the fuel itself. Finally, to differentiate this work from other similar papers, Canada-specific environmental considerations, such as the effects of extreme cold temperatures and ice and snow were also studied.

1.4 Limitations

The properties, attributes and limitations of DME as an on-road fuel will be compared to the properties of conventional diesel, propane (LPG), liquefied natural gas (LNG) and compressed natural gas (CNG). Very little consideration will be given to comparisons between DME and gasoline and solid fuels since they are essentially not used in the heavy haul industry in Canada. Additionally, the scope of this work included considerations for operational costs and tailpipe emissions and did not include an in-depth ‘well to wheel’ economic and emissions analysis.

It is challenging to present a literature review without drawing comparisons between fuels that compete with one another for share in a competitive marketplace. Nonetheless, the intent of this report was not to rank the various fuels against one another. Rather, the information will be presented such that the reader may better understand the various attributes of each the fuels without rankings.

No new development or testing was performed by the NRC to generate the content of this report. Rather, it is a compendium of many other academic, and industry relevant work previously conducted by others.

1.5 Methodology

In order to present all of the relevant DME data and information, NRC-AST embarked on an exercise to collect as much material as possible regarding all of the topics required in the project’s statement of work. In order to do this, NRC-AST used the services of NRC’s Knowledge Management (KM) group to retrieve as many DME related journals, papers, presentations, test results and dissertations from academics as well as marketing and specification documents from the commercial trucking sector. Although much of the information was retrieved from worldwide academic papers, care was taken to not focus entirely on the chemical properties of DME. Rather, the theory was blended with the industry-specific requirements that were pertinent to the heavy haul sector in Canada to form a study that can be used to fully understand how DME can be used in Canada. More importantly, any of the limitations that must be understood by operators, drivers, refuellers, government regulators and the motoring public have also been explored.

In all, over 80 papers, presentations and industry documents formed the basis of the references for this research study.

Unless otherwise stated, any reference to “diesel” or “conventional diesel” refers to the grades of #1 and #2 diesel that are found at fuel stations as seasonally adjusted pump fuel. This does not include biodiesel or other alternative fuels. Those fuels have been described and presented separately, as necessary.

2 REVIEW OF DIESEL EMISSIONS

2.1 Emissions

A review of diesel emissions, and their effects on the environment and human health, will allow the reader to better understand the current state of diesel engine emissions and compare that to the emission reduction concepts and potential presented for DME. The emission concepts of gasoline engines have not been presented.

There are a variety of pollutants that enter the atmosphere when any fossil fuel powered vehicle is operated. The transportation sector is a major contributor to air pollution with the burning of diesel being one of the most significant. Health impacts from short term exposure to diesel emissions range from eye, throat and lung irritation to exacerbated asthma and pneumonia symptoms. Long term exposure can include decreased lung function, arrested lung development and cancer.

In Canada, Environment Canada is responsible for drafting the standards that are used to regulate tailpipe emissions from both the on-road and off-road sectors. These standards are generally harmonized with those of the United States Environmental Protection Agency's (EPA). A complete analysis and presentation of the EPA's emission reduction strategies is outside the scope of this document but it can be described as a series of increasingly stringent regulations and standards aimed at reducing tailpipe emissions for both the on-road and off-road sectors (among others). For example, the current EPA Tier 4 regulated tailpipe emission standards specify the maximum amount of certain pollutants allowed in exhaust gases discharged from heavy duty off-road vehicle engines. Similar strategies and regulations exist for on-road diesel engines and are referred to as Air Pollutant Regulations and GHG standards. Table 1, extracted from a Massachusetts Bay Transportation Authority (MBTA) hybrid bus study [6] and the government of Canada's climate change website [7], outlines some of the major pollutants and describes their sources and possible effects on the environment and the health of humans and animals exposed to the exhaust.

Table 1 – Exhaust Pollutants

Pollutant	Source	Environmental and Health Effects
Hydrocarbons (HC)	Unburned or partially burned fuel	Certain hydrocarbons are known to be carcinogenic or toxic.
Carbon Monoxide (CO)	Incomplete combustion	Carbon monoxide can produce severe poisoning and/or death because it binds with hemoglobin in the blood, impairing its ability to transport oxygen.
Oxides of Nitrogen (NO_x)	Reactions between oxygen and nitrogen	NO by itself is harmless. However, the oxidization to NO_2 can irritate lung tissue. NO_2 also combine with water to form nitric acid which can damage trees and other plants. Nitrogen oxides have also been categorized as a precursor to smog forming ozone.
Particulate Matter (PM)	Product of combustion from	Scatters light, reducing visibility. Can be ingested into the lungs, which can be

	diesel engines	harmful to human health.
Carbonyl Compounds (Acetaltehyde, formic acid and formaldehyde etc)	Reactions with oxygen	May cause irritation to the eyes, skin and respiratory systems. Listed as a probable carcinogen but further study is required.
Carbon Dioxide (CO_2)	Complete combustion	May not have direct short term health impact to humans but is described as the main cause of human induced climate change according to the Canadian federal government's climate change website [7].

The first five products of combustion listed in Table 1 can be reduced with engine and fuel injection tuning and/or the addition of emission control devices in or on the engine, or downstream of the engine. Engine manufacturers worldwide have achieved significant reductions (90% reduction in NO_x, for example) by adhering to the current North American, European and Japanese regulations shown in Table 2. [8] [9] [10] [11]

Table 2 – Current EPA, Japanese and European limits for heavy duty vehicles

Pollutant	**Japan 2016 (g/kWh)**	**EPA On Road* (g/kWh)**	**2014 EPA Tier 4 (g/kWh)***	**Euro V (g/kWh)*****	**Euro VI (g/kWh)******
Carbon Monoxide (CO)	2.22	20.79	3.50	1.50	1.50
Hydrocarbon (HC)	0.17	0.19	0.19	0.46	0.13
Oxides of Nitrogen (NO_x)	0.40	0.27	0.40	2.00	0.40
Particulate Matter (PM)	0.01	0.01	0.02	0.02	0.01

* Converted from standard published in g/bhp-h with possible round off error
** 130 kW (174 hp) to 560 kW (750 hp) off-road engines
***ESC: European Stationary Cycle
****WHSC: World Heavy Duty Transient Cycle

Table 2 lists the current limits for CO, HC, NO_x and PM. For many years, Carbon dioxide (CO_2) production was considered a non-regulated emission by the US EPA and Environment Canada since the only way its production (and hence influence on the environment) can be reduced is by burning less fuel or by burning a different type/grade of fuel (thus not included in Table 2). However, the US EPA and Environment Canada have recently begun regulating the emissions of CO_2 (i.e. fuel consumption) via Greenhouse Gas Heavy Duty Vehicle emission standards, starting with model year 2014 vehicles. The regulations restrict the amount of CO_2 that can be emitted from new engines, and are being phased in starting from 2014. In the US, credits and banking of credits will also be allowed if OEMs can demonstrate overall aggregated compliance for all the vehicles they are producing in that particular model year. The exact calculations for credits and banking are beyond the scope of this document. The current CO_2 limit standard established in Canada for Class 8 tractors is set at 637 g/kWh (475 g/bhp-hr) beginning with model year 2014 and will be reduced to 617 g/kWh (460 g/bhp-hr) for the 2017 model year. [12]

As an example, Table 3 lists engine power, in kW, along the top row and a range of fuel consumption, in litres/100 km along the left column. All highway rated engines can be characterized by these pairings, at any given time when tested on a chassis dynamometer. Each of the cells in the table represents the calculated value of CO_2 emissions, in g/kWh, for that paring of fuel consumption and rated engine power. A sample calculation is shown as follows and a similar table is shown in Section 3.2.6.4 for DME:

((40 l/100 km*2.64 kg/litre * 105 km/hr)/279.64 kW)*10 [1]

Where:

- The vehicle speed is assumed to be constant at 105 km/hr;
- The vehicle fuel consumption is constant at 40 l/100 km; and
- The tractor's engine is rated at 280 kW (375 hp);

In a real emissions test, the vehicle would be subject to the standardized drive cycle on which the emissions standard was based and the value for engine power would be measured instantaneously using a dynomometer. This sample example calculation assumes a constant speed and power and is not representative of a real drive cycle test that would be used for compliance, but is still useful for the comparisons being made between diesel and DME.

The values shown in yellow are below Environment Canada's standards (i.e. a pass) whereas the values in blue are above the standards (i.e. a fail). The three values shown in green are pairings that would be below the current standards but above the 2017 standards. All of the values shown in the Table are meant to represent an individual vehicle result and do not reflect any form of credit or banking scheme as described in Section above.

Table 3 – CO_2 emissions for various power and fuel consumption pairings, 105 km/h

CO_2 emissions (g/kWh) using pump diesel									
	Power	Engine Power							
	hp	375	400	425	450	475	500	525	550
	kW	280	299	317	336	354	373	391	410
Average Fuel Consumption (l/100 km)	40	396.51	371.73	349.87	330.43	313.04	297.39	283.22	270.35
	45	446.08	418.20	393.60	371.73	352.17	334.56	318.63	304.14
	50	495.64	464.66	437.33	413.04	391.30	371.73	354.03	337.94
	55	545.21	511.13	481.06	454.34	430.43	408.90	389.43	371.73
	60	594.77	557.60	524.80	495.64	469.56	446.08	424.84	405.53
	65	644.34	604.06	568.53	536.95	508.69	483.25	460.24	439.32
	70	693.90	650.53	612.26	578.25	547.82	520.42	495.64	473.11
	75	743.46	697.00	656.00	619.55	586.94	557.60	531.05	506.91
	80	793.03	743.46	699.73	660.86	626.07	594.77	566.45	540.70
	85	842.59	789.93	743.46	702.16	665.20	631.94	601.85	574.49
	90	892.16	836.40	787.20	743.46	704.33	669.12	637.25	608.29
	100	991.28	929.33	874.66	826.07	782.59	743.46	708.06	675.88
	105	1040.85	975.80	918.40	867.37	821.72	780.64	743.46	709.67
	110	1090.41	1022.26	962.13	908.68	860.85	817.81	778.87	743.46
	115	1139.98	1068.73	1005.86	949.98	899.98	854.98	814.27	777.26
	120	1189.54	1115.20	1049.60	991.28	939.11	892.16	849.67	811.05

The calculations for Table 3 are relatively straight forward because any diesel engine burning pump diesel will produce approximately 2.64 kg of CO_2 for every litre of fuel it burns. [13] This can be compared to gasoline engines which produce approximately 2.34 kg of CO_2 for every litre consumed. However, diesel engines usually burn less fuel per km than similarly sized gasoline engines, and therefore the more relevant measure is not the mass produced per litre burned, but rather the mass produced per distance traveled (e.g. grams/km or grams/mi). A similar table for any other pollutant would be difficult to produce mathematically since the levels of emissions cannot be predicted with the same certainty as CO_2.

Unlike say, NO_x, no amount of exhaust gas re-circulation, scavenging or catalyzing can directly reduce the CO_2 production rate for any particular engine burning a particular type of fuel. However, changing to a different grade of fuel can reduce CO_2 production. For example, rapeseed based biodiesel produces about 2.49 kilograms of CO_2 per litre of burned fuel. Once again, it must be stressed that these are tailpipe emissions. Studies by Argonne National labs and the US National Renewable Energy Laboratories have concluded that biodiesel's actual CO_2 footprint can be less than half that of conventional diesel when the levels of CO_2 captured by the plants, from which the bio fuels are manufactured, are also considered. [14] Additionally, reducing aerodynamic drag and rolling resistance can reduce fuel consumption and CO_2 emissions from moving vehicles, which allows manufacturers to meet the current GHG standards, however, they have no effect on vehicles that are idling. It is estimated that nearly eight billion litres of diesel fuel [15] are consumed in the United States alone for tractor idling. Since DME's physical and chemical properties are significantly different than those of diesel fuel it will be of interest to determine how the use of DME could affect tailpipe emissions of CO_2 not only for moving vehicles, but for vehicles that are idling where aerodynamic drag and rolling resistance reductions have no effect.

The monitoring of the carbonyl compounds listed in Table 1 is treated somewhat differently than the pollutants already discussed. Oxygenated compounds such as acetaldehyde, formaldehyde, formic acid etc form part of what are known as the Non Methane Organic Group (NMOG). These compounds are generally considered to be non-hydrocarbon based pre-cursers to ozone. The EPA's current on-road heavy duty diesel exhaust emission standards do not explicitly include NMOG [10] measurements but they do refer to Non Methane Hydrocarbons (NMHC). However, these regulations refer to compression ignition engines burning conventional diesel fuel which have inherently low levels of NMOG. In general, most NMOG calculations are paired with NO_x. For example, the current EPA Tier 3 light duty vehicle regulations include new "NMOG + NO_x" limits that dictate the average fleet wide emissions levels for any given manufacturer. These new limits apply to model year 2017 and become progressively more stringent until 2025. [16] It will be important to determine if the emissions produced from burning DME in a compression ignition engine would warrant the measurement of NMOG (either by itself or combined with NO_x) as is currently performed with fuels with more than 25% ethanol content, for example. Levels of NMOG above a pre-determined threshold that result from burning DME could necessitate a revision to the current EPA and EC standards for compression ignition heavy duty engines.

Although diesel engines produce all the emissions listed in Table 1, the two types that have been most closely monitored in the diesel engine industry are NO_x and PM since diesel engines operating without any type of emission control devices inherently produce high levels of these two pollutants when compared to gasoline engines of similar size. Potentially reducing these emissions is one of the reasons that DME is being studied as an alternative to diesel.

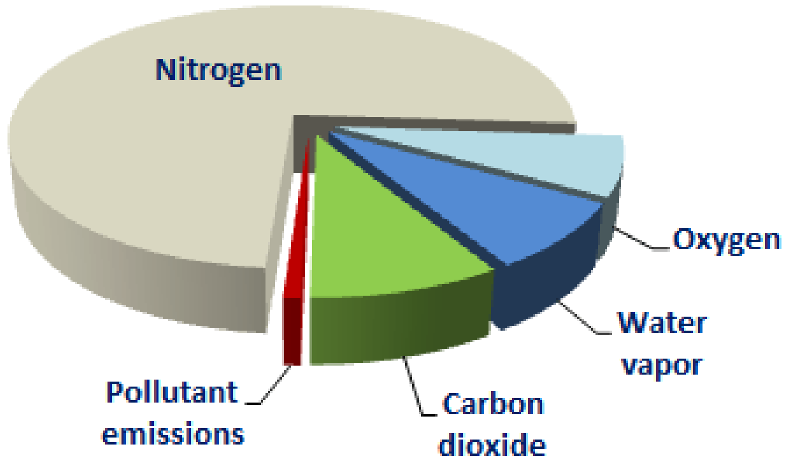


Figure 1: Diesel exhaust composition

Figure 1 illustrates the breakdown of all products that are emitted from a diesel engine. The first five items in Table 1 are all contained within the red slice of the chart whereas the sixth item, CO_2, is represented by the light green. All the other slices are considered harmless emissions. It will be important to determine how the use of DME could affect the emissions within the red and CO_2 slices of the chart and what type of add on equipment would be required (if any) to maintain compliance with current Environment Canada (and EPA) pollutant regulations and the recently adopted GHG reduction standards.

2.2 Current Emission Reduction Technologies

A thorough description of all emission reduction strategies and their internal workings is far beyond the scope of this document. However, there are some technologies and inter-relationships between technologies that will require some explanation in order to allow the reader to make better sense of some of the academic results presented in this report.

In general, there are four important technologies that must be understood for the purposes of this study: Selective Catalytic Reduction, Exhaust Gas Recirculation, Diesel Oxidation Catalysts and Diesel Particulate Filters/Traps. A brief description, taken from the NRC's Future Vehicles Concept Study, [13] of each technology is provided:

2.2.1 Selective Catalytic Reduction

Selective Catalytic Reduction, or SCR, is a well established means of reducing exhaust Nitrogen Oxides (NO_x) to levels below those currently required by Environment Canada regulations. A properly functioning SCR system can reduce NO_x levels by 80% to 90% depending on the temperature of the exhaust stream. SCR has been used for many years in the stationary power generation industry and has been successfully implemented in recent years on medium and heavy duty diesel powered vehicles in North America, Asia, Australia and Europe. SCR does not directly affect the power output, fuel consumption or other performance measures of the engine and is not a primary countermeasure used to reduce emissions other than NO_x, although slight particulate matter reductions are possible as a secondary effect (see Section 2.2.4). SCR reduces NO_x with the aid of a reductant and a catalyst, into diatomic Nitrogen (N_2) and water (H_2O), two compounds that are abundant and harmless to the environment. Current on-highway engines use a reductant mixture of urea ($(NH_2)_2CO$) and water (32.5% urea dissolved in de-mineralized water is typical). This mixture is then injected into the exhaust stream and the resultant urea/water/exhaust gas is absorbed into a catalyst. The SCR catalysts are normally manufactured from a variety of ceramics and precious metals, each having their own advantages, disadvantages and operating temperature ranges. The amount of urea mixture added to the exhaust stream varies, however, it is currently between 2% and 6% of the fuel burned depending on the source cited. [17] [18] [13] The mixture is injected into the exhaust stream by a dosing meter (the Control Unit under the Diesel Exhaust Fluid Tank in Figure 2) which accurately dispenses the mixture based on fuel flow information from the engine's ECU.

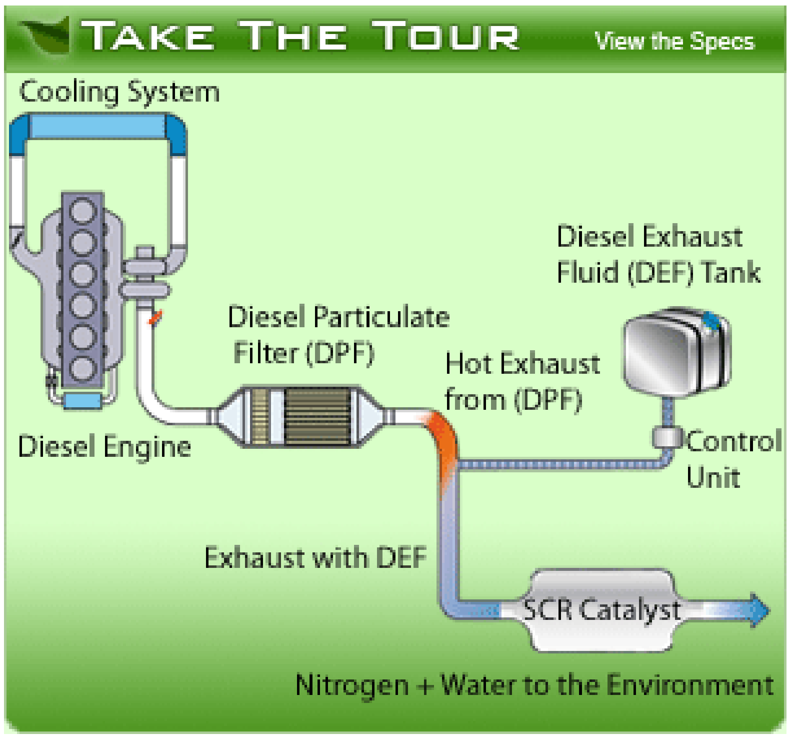


Figure 2: Example of SCR components (http://www.truckscr.com/)

If a highway tractor, for example, is refueled with 400 L of diesel, there is a requirement to fill a separate on board tank with approximately 20 L of urea and water mixture. The current practice for highway tractors is to carry enough urea mixture to allow refilling with every third or fourth diesel re-fuel. Therefore, each vehicle requires a separate tank that could hold between 40 L and 100 L of urea mixture, depending on the size of the engine and the desired filling frequency. The position and shape of the urea tank are not critical but the tank is normally positioned relatively close to the existing diesel tank for filling convenience. The density of the urea and water mixture is approximately 1089 kg/m^3 at 20°C and 101 kPa, slightly heavier than water (1000 kg/m^3). Therefore, a filled SCR tank typically adds between 40 kg and 110 kg to the total weight of the vehicle. The combined mass of all the SCR components, including the filled tank, is typically between 150 kg and 200 kg.

2.2.2 Exhaust Gas Recirculation

Conventional exhaust gas re-circulation (EGR) has been used for many years on many types of internal combustion engines, both gasoline and diesel. It is a means of reducing emissions by re-directing a portion of the exhaust stream back into the combustion chamber for re-burning. Cooled exhaust gas re-circulation is a modified version of EGR whereby the exhaust that would normally be directly fed back into the combustion chamber (i.e., conventional EGR) is first sent to an air-to-water heat exchanger for cooling. The introduction of cooled exhaust back into the combustion chamber results in a cooler combustion process which reduces the production of NO_x. A typical system can divert from 5% to 30% of the engine's exhaust back into an air to-water heat exchanger then back into the engine's combustion chambers. This reduces the peak temperatures inside the combustion chamber as well as the oxygen concentration in the intake air, thus reducing the formation of NO_x. Unlike urea injection/SCR systems, the cooled EGR engines do not require the addition of any consumable product and do not require operator or maintainer input as long as all the components are in good working order. However, the addition of cooled EGR may require more complicated and expensive hardware such as variable geometry turbochargers to allow for a continuous adjustment of exhaust manifold pressure and boost pressure. Additionally, if cooled EGR is the only method being used to reduce NO_x in a large diesel engine, there may be a requirement for so-called 'massive EGR' which diverts as much as 50% of the exhaust stream gases back into the engine.

The downsides to such an approach include engine power de-rating or the need for dual turbochargers or superchargers to make up for lost power that results from such a high level of exhaust gas re-circulation. The increased flow of exhaust gases may also increases in-cylinder pressures and the introduction of exhaust gas back into the combustion chamber potentially increases engine wear since products of combustion such as sulfur oxides have been linked to engine wear [13]. Studies have shown a strong relationship between sulfur oxides in engine oil and the amount of EGR. [13] For these and other reasons, most major engine manufacturers have elected to meet the current EPA/EC standards with SCR, rather than massive EGR.

The use of EGR adds approximately 15 kg to 40 kg to the weight of a tractor. There is no change to the available space claim or payload space on the vehicle because the EGR equipment is located under the hood, rather than behind the cab or along the frame rails. Therefore EGR is an attractive option for operators who tend to 'cube' out their trucks or who do not want to refill urea tanks.

2.2.3 Diesel Oxidation Catalysts

Diesel Oxidation Catalysts, or DOC, consist of a honeycomb monolith substrate coated with platinum group catalyst surrounded by a stainless steel shell container. The honeycomb interior allows a very large contact area over which the exhaust gases may flow. As the hot exhaust gases pass over the honeycomb, many harmful gases are converted into harmless by products such as water and carbon dioxide. A properly functioning diesel oxidation catalyst can reduce carbon monoxide levels and hydrocarbons by 90%. However, a counter-productive effect can take place at certain higher gas temperatures and fuel sulfur content whereby the gases exiting the catalyst contain high levels of sulfuric acid and the treated exhaust is no less harmful than the gases exiting the engine upstream of the catalyst. It is for this reason that diesel oxidation catalysts are most beneficial when used with low sulfur fuels which are now the industry standard. A typical heavy duty vehicle DOC weighs 30 kg and resembles a large cylindrical muffler.

2.2.4 **Diesel Particulate Filter and Traps**

Methods to reduce emissions from within the engine or from the fuel itself are normally referred to as primary countermeasures. These may include EGR, O_2 sensors or SCR as described in Section 2.2.1. Primary methods are normally active and form part of the feedback loop used by the engine control module (ECM). Methods that occur downstream of the engine are called secondary countermeasures and are normally passive – they do not form part of the feedback loop to the ECM and, as such, do not normally affect fuel consumption unless they are severely blocked. Diesel particulate filters (DPFs or "traps") are secondary countermeasure devices normally installed inline with the exhaust system well downstream of the engine and are used to remove particulate matter and soot from a diesel engine's exhaust stream (e.g., Figure 4-3). The addition of the trap does not improve (or even alter) the performance of the engine but it does drastically reduce the amount of particulate matter released into the atmosphere. Current traps can reduce particulate matter emissions by as much as 95% and are therefore used to comply with worldwide emission reduction strategies similar to those outlined in Section 2.1.

Many newer, more advanced traps require the use of low-sulfur diesel to be effective. Traps, by nature, tend to accumulate particulate matter and soot to the point where the exhaust system becomes restricted which then affects engine back pressure and performance. In order to circumvent this build up and subsequent restriction, most traps use a process called regeneration. Regeneration is normally accomplished by the addition of heat into the trap which in turn burns off the particulate matter. A typical trap will require its temperature to be elevated from 400°C to at least 600°C in order to reach the particulate self-ignition state. The temperature is maintained at the self-ignition state until such time as most, or all, of the particulate has been removed. However, the use of heat to remove the PM has two drawbacks. The first is that added heat must be generated via energy delivered by the engine, which results in lost efficiency for the engine. The second is that significant thermal stresses are added to the casing of the trap as its temperature cycles back and forth, and this can lead to cracking and leakage. To alleviate these situations, manufacturers have begun using catalytic regenerative traps. [13] Catalytic regenerative traps remove particulate matter from the exhaust stream and then eliminate them by a catalytic process that usually involves the introduction of some element such as calcium, vanadium or copper. The inclusion of the catalyst lowers the burn temperature of the particulate matter and the PM is therefore eliminated without the need for added heat or energy. The principal drawback of catalytic removal is the need to replace the catalyst at regular intervals once they have become 'poisoned' by the exhaust stream.

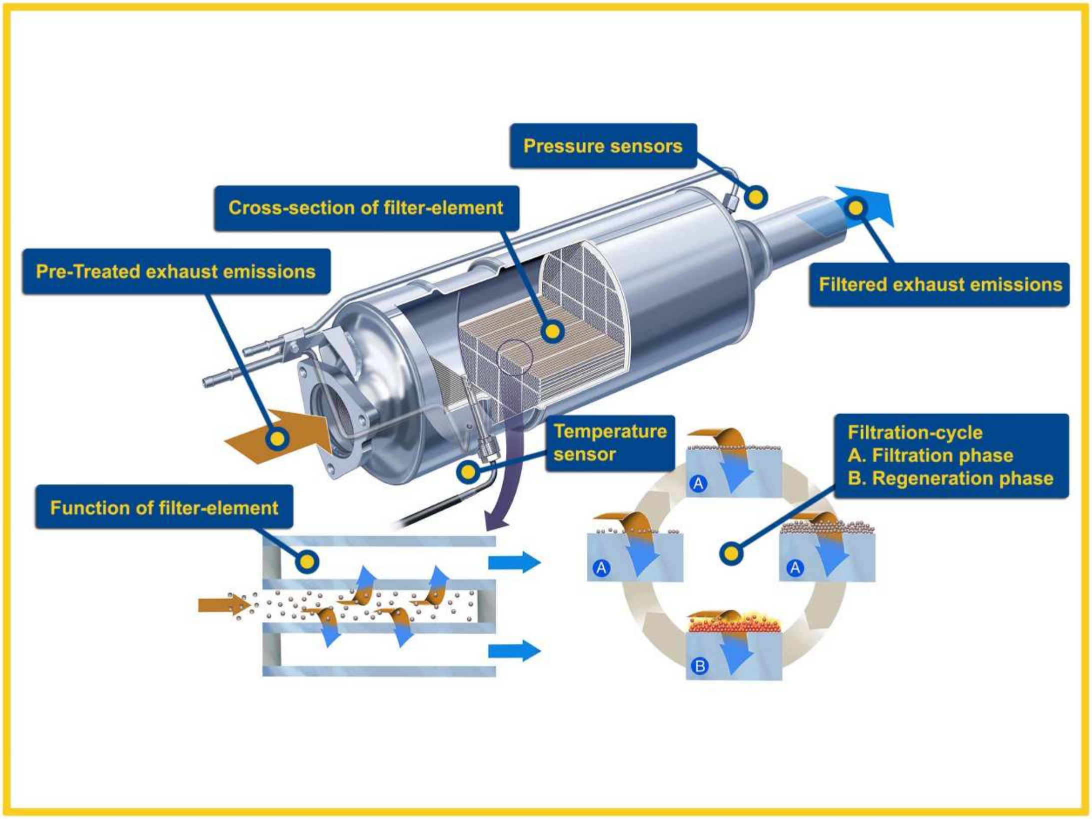


Figure 3: Diesel Particulate Filer (Courtesy of motoringassist.com)

Biodiesel fuel and seed oils contain by products and natural catalysts that reduce the particulate burn-off temperature by as much as 50°C, which would potentially reduce the maximum temperature inside the heated traps and therefore reduce the negative side effects discussed above.

Traps tend to be fairly large and require suitable space to be housed within a vehicle's exhaust system which can compromise space claim and reduce payload. Most diesel traps add approximately 30 to 50 kg to the weight of a vehicle.

2.2.5 **Inter Relationship Between Reduction Devices**

Although each of the four technologies was described separately, there are some relationships between the devices that must also be understood. The most notable relationship being that of in-cylinder temperature and NO_x reduction. There are two basic methods to reduce NO_x from a diesel engine: lowering in-cylinder temperatures via the use of some level of EGR or treating the exhaust after exiting the engine with SCR. If an engine manufacturer elects to lower NO_x by using SCR, there is a secondary effect other than the intended NO_x reduction downstream of the engine. SCR is so effective at reducing NO_x it allows for higher in cylinder temperatures which in turn burns off more hydrocarbons and PM and can lead to a more efficient combustion process. Therefore, installing SCR on a vehicle will result in the desired NO_x reduction as well as some secondary upstream reductions of PM and HC but these reductions are typically not sufficient to reduce the HC and PM pollutant levels to below the required limits thus requiring the use of DOCs or DPFs for full compliance. Stated another way, SCR does not itself reduce the PM content of the exhaust stream, rather, its presence can reduce the amount of PM before the exhaust stream even enters the SCR componentry due to higher temperatures in the engine. In addition, the reduced PM levels caused by SCR may cause fewer regeneration cycles of the heated diesel particulate filter which in turn reduces fuel consumption and CO_2, slightly.

The use of DME could result in a shift of exhaust emission composition compared to diesel thus allowing or requiring changes to engine add on devices and/or after treatments. It will be important to understand the inter relationships between the various devices such that designers and operators can understand which devices could be removed to optimize their vehicle configurations, with respect to weight and space claim, while still maintaining compliance with federal emissions regulations.

3 PROPERTIES OF DME

The following sections describe the physical, chemical and biological properties of DME, independent of the trucking sector.

3.1 How is DME Produced

Conventional diesel fuels are generally produced as fractional distillates of petroleum fuel oil and therefore must be produced from crude that is extracted from the earth or the seabed. However, DME can be derived from: [19] [20]

- Natural gas;
- Crude oil;
- Propane;
- Residual oil;
- Pulp and paper waste;
- Agricultural by-products;
- Municipal waste;
- Fuel crops such as switchgrass;
- Coal, and
- Biomass such as forest products and animal waste

Unlike conventional diesel which is produced from non-renewable crude oil, DME can be produced anywhere using renewable products like some of the items in the bulleted list above. This provides a great deal of flexibility for production since facilities do not need to be located near sources of crude oil but can be setup any place where bio based feedstocks or natural gas can be found, or produced.

DME has been used in a variety of industrial processes and propellants for years and interest in DME as a fuel for vehicles is also increasing, at least in some countries, "since it can provide energy for large amounts of work both per unit land used to cultivate feedstocks, and per unit energy used to produce it". Salsing et al went on to state that "very few (if any) other alternative fuels can propel vehicles so far, using as little land as DME, mainly because the production process is highly efficient". [21]

The literature review revealed more methods for DME fuel production than should be described in this document. In general though, DME is produced via the dehydrogenation reaction of methanol, which is made from synthesis gas with carbon monoxide and hydrogen as the main components [19]. Based on current projections, it is likely that the abundance of North American natural gas and a high level of animal waste will provide ample sources for future DME production [22] without reliance on offshore resources. It takes approximately 1.4 tons of Methanol to produce approximately 1.0 ton of DME. [22]

One novel method which started in 2008, involved a 40 million dollar two year research study that demonstrated how DME can be produced from the gasification of a feedstock called black liquor (BL). The BioDME project objective was described as a "Demonstration of an environmentally optimized future biofuel for road transport covering the full chain from production of fuel from biomass to the utilization in vehicles." [1] Black liquor is a by-product of the pulping process that can be gasified and then converted to DME via syngas [1], as shown in Figure 4. The project was then converted into an industry feasibility field test involving ten heavy duty trucks, all operating on DME produced from the project, and all performing revenue service with loads. The detailed results of the field testing are presented in 7.3.

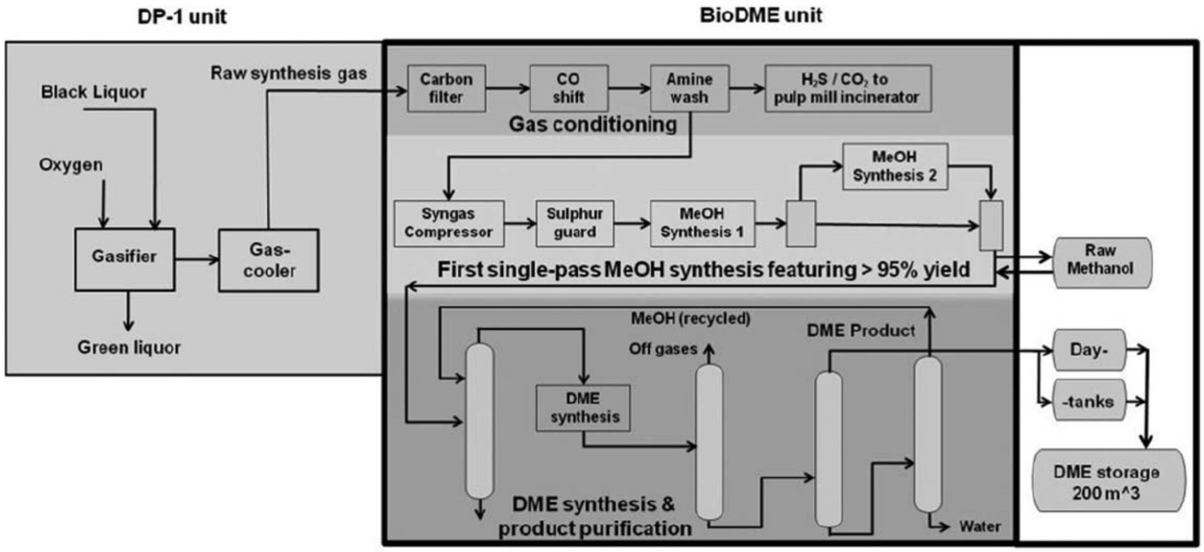


Figure 4: Block diagram of black liqor syngas conversion process [1]

According to the researchers, BL from a pulp mill is normally a very stable feedstock with small deviations in composition over time thus making it an excellent product for the conversion process. [1] The DME production of the pilot was mainly governed by the rate of feed flow to the unit. Before designing the unit, the rate of raw syngas to the processing unit was estimated to be approximately 870 kg/h and on this basis a DME production rate of 168 kg/h, corresponding to 4 tonnes/day of DME was anticipated [1]. Gasification of BL with oxygen was carried out at 30 bar and the methanol synthesis pressure was 130 bar [1]. A closer inspection of the pilot data led to the conclusion that approximately 90% of the theoretical conversion of synthesis gas to DME was typically attained during normal operation and that all commercial catalysts and reactors performed well and in keeping with predictions [1]. The plant was operated using but two employees per shift and showed good performance, following the ISO standards currently under development (Section 0). The longest continuous period of operation had been 26 days which ended with a planned shutdown. [1] A year after the BioDME-project started the host pulp mill changed its operating procedure for the BL system, which led to a significant decrease in energy content of the BL compared to the design value. The main reason for this change was the addition of more ash to the BL [1]. The rest of the chemical details of the process are outside the scope of the document.

This is but one example of how DME can be produced from a renewable by-product from another industrial process rather than from non-renewable crude that must be extracted from the earth. Although the abundance of natural gas may make it most economically viable to produce DME from natural gas in the near term, DME can also be produced from products that are normally treated as waste from other processes.

3.2 Chemical and Physical Properties of DME

DME is a liquefied organic compound gas that can be stored in a manner similar to pressurized home barbeque propane and other LPG products. DME exists as an invisible gaseous ether compound under atmospheric conditions (0.1 MPa and 298 K) but must be condensed to the liquid phase by pressurization above its vapour pressure at about 0.5 MPa (5.1 bar/73 psi) at 25 °C [19] to be used as a diesel fuel alternative. Like propane, DME is heavier than air (see Section 9.2.1). Although the principal focus of this study relates to heavy haul diesel engines, DME has been used for decades in a variety of products and applications such as propellants in aerosol cans, solvents and medical treatments due to its lack of toxicity and its ability to be absorbed into the troposphere and, in Asia, as a cooking fuel. [2] DME is considered a refrigerant with ASHRAE refrigerant designation R-E170 and is also used in refrigerant blends with butane and propene. DME, when stored at 5.1 bar, is not a cryognenic product therefore storage and handling are much simpler than other products that require special vessels and safety equipment. Issues relating to tank storage are discussed in greater detail in Section 6.2.1.

The fuel's basic chemical properties, independent of the trucking industry, are shown in Table 4 and many of these properties have been discussed in greater detail in Section 3.2.1 through Section 3.2.7.

Table 4 – Properties of DME and diesel fuel [19]

Fuel property	Unit	DME (dimethyl ether)	Diesel
Chemical structure		$CH_3{-}O{-}CH_3$	–
Molar mass	g/mol	46	170
Carbon content	mass %	52.2	86
Hydrogen content	mass %	13	14
Oxygen content	mass %	34.8	0
Carbon-to-hydrogen ratio		0.337	0.516
Critical temperature	K	400	708
Critical pressure	MPa	5.37	3.00
Critical density	Kg/m^3	259	
Liquid density	Kg/m^3	667	831
Cetane number		>55	40–50
Auto-ignition temperature	K	508	523
Stoichiometric air/fuel mass ratio		9	14.6
Boiling point at 1 atm	K	248.1	450–643
Lower heating value	MJ/kg	27.6	42.5
Modulus of elasticity	N/m^2	6.37E+08	14.86E+08
Kinematic viscosity of liquid	cSt	<0.1	3
Surface tension	N/m	0.012	0.027
Vapor pressure	kPa	530	<<10

3.2.1 **Carbon, Oxygen and Hydrogen Content**

The chemical composition of DME is CH_3-O-CH_3 and is shown in Figure 5. One of the more significant features of DME is the lack of a direct carbon-to-carbon bond that is found in traditional diesel fuels. Particulate Matter, or soot formation, in a DME-fueled engine is almost zero because DME is an oxygenated fuel with an oxygen content of 35% by mass and no carbon-to-carbon bonds [19] whereas conventional diesel contains no Oxygen but does contain carbon-to-carbon bonds. The increase in oxygen content can reduce the precursors to soot formation like C_2H_2, C_2H_4 and C_3H_3. The presence of oxygen can also reduce auto ignition since the C-O bond energy is lower than the C-H bond energy found in conventional diesel. Additionally, the carbon to hydrogen ratio in DME is approximately 65% of that found in conventional diesel fuels. As a result, both soot suppression and rapid diffusion combustion of DME fuel result in nearly zero soot emissions. [19].

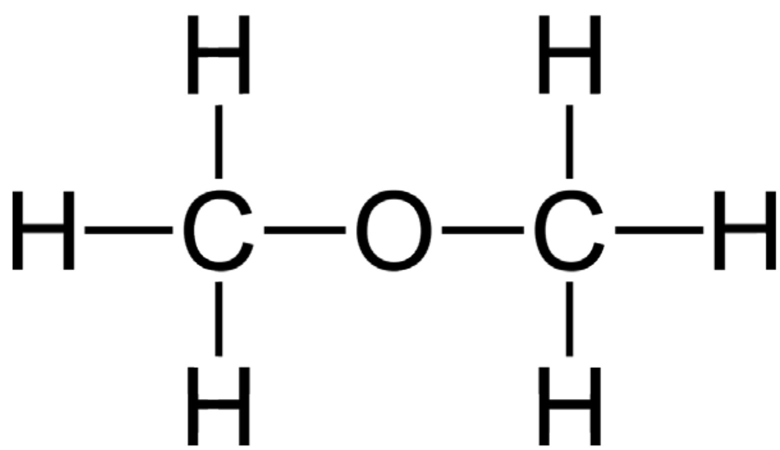


Figure 5: Chemical composition of DME showing lack of C-C bond

The air/fuel ratio of DME fuel at stoichiometric conditions is given by $(ma/mf)_{st}$ = 14.28 mol-air/mol-fuel (DME) or 8.99 kg-air/kg-DME (versus 14.6 kg-air/kg-diesel) meaning that complete combustion of 1 kg DME requires less air than that of 1 kg diesel fuel. [19] However, more than 1 kg of DME is required to provide the same amount of energy (Section 3.2.4) as 1 kg of diesel. The amount of air required is approximately 61% that of diesel but the heating value of DME is only 67% of diesel. DME has a much higher, and wider, flammability range (i.e. the volume of fuel, expressed as a percentage in an air mixture at standard conditions, where ignition may occur) in air than the three hydrocarbon fuels (gasoline, diesel and propane) [23] but very similar to natural gas, as shown in Table 5. Finally, DME is sulfur free whereas even ultra-low sulfur diesel (ULSD) contains some sulfur. [24] Not only is sulfur an environmental pollutant, but some devices such as regenerative diesel particular filters (see Section 2.2.4) will not function correctly with high sulfur fuel. Conversely, older diesel engines require higher sulfur content fuel to provide lubrication to sealing material, which has been discussed in great detail in Section 3.2.3.

Table 5 – Flammability limits of various fuels

Fuel Type	Lower and Upper Flammability Limits (Volume % in air)
DME	3.4 to 18
Diesel	0.6 to 7.5
Gasoline	1.4 to 7.6
Natural Gas	4.4 to 17
LPG	2.1 to 10.1

3.2.2 **Cetane Number**

Gasoline is generally rated by its octane level (Table 6) whereas fuels used in diesel engines are measured by their cetane number (CN) (Table 4). The cetane number is a measure of the combustion speed of a diesel fuel (in other words the inverse of a fuel's ignition delay). [8a] Fuels with a higher cetane number will have a shorter delay between the moment of injection and ignition. The use of lower cetane numbered fuels tends to cause undesirable knocking in diesel engines which can cause engines to sound loud and run roughly and in some cases causing unburned fuel to travel into the exhaust port before ignition can occur. DME also evaporates faster than diesel fuel which contributes to improved mixing characteristics of fuel and air. Therefore, the unburned mixture remaining during the combustion period is less than that remaining with diesel, which in turn reduces HC formation [19] (see Section 3.2.6.3). Park and Lee [19] concluded that DME evaporation was faster than the evaporation of light oil and resulted in a more evenly distributed leaner spray inside the cylinders. All of these attributes combine to form a fuel that can, theoretically, combust more completely than conventional diesel.

Historically, cetane number was calculated in a lab using a specialized test engine called a cooperative fuel research (CFR) engine and a fairly complex test method. Because using dedicated engines and processes or instruments for real fuel tests is painstaking, expensive and time consuming, many fuel formulators use a "calculated" method to determine cetane numbers. Two common tests are ASTM D976 and ASTM D4737. These two tests use fuel density and boiling/evaporation points to derive cetane ratings [100] and can be used to calculate the cetane number. Variations in test method can result in a printed range of cetane number for DME rather than an exact value. [1] [2] [19] [24] [25]

Fuels with higher cetane numbers tend to burn more quickly and allow more time for the complete combustion process. In North America, most #1 and #2 pump diesel fuels have cetane numbers between 40 and 45 and many bio-diesels have CN greater than 50, as shown in Figure 6. [2] [26]

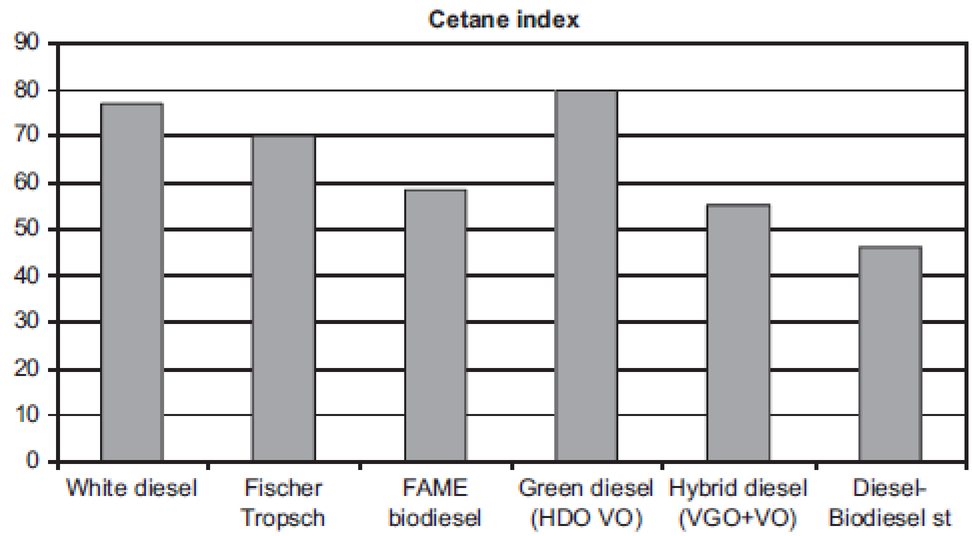


Figure 6: Cetane number for various diesels [26]

Fuels such as propane and natural gas have octane numbers higher than 100 but cetane numbers less than 10 [26] making them impractical for dedicated use in a diesel cycle engine. These fuels have been adapted for use in heavy haul vehicles but can only be burned in a spark ignition engine. Cummins Westport does offer a dual fuel natural gas compression ignition engine, however, it requires approximately 40% (by energy content) diesel to be mixed with natural gas [27] and cannot function without diesel fuel as the ignition source. The natural gas is introduced upstream of the cylinder and then diesel is injected directly into the cylinder near the end of the compression stroke which ignites the diesel and the natural gas. This system is shown in Figure 7. Cheenkachorn et al [28] performed testing on engines burning pure diesel as well as dual fuel diesel/LNG engines. They concluded that the dual fuel engines were very sensitive to knocking, depending on the ratio of diesel to natural gas (which in their study never exceeded 77.90% natural gas). They also discovered that power output from the hybrid natural gas/diesel fuel engine was comparable to that of pure diesel. Their emissions results showed that, compared to diesel operation, the dual fuel engine operation showed higher THC and CO emissions, while the emissions of NO_x and CO_2 were lower.

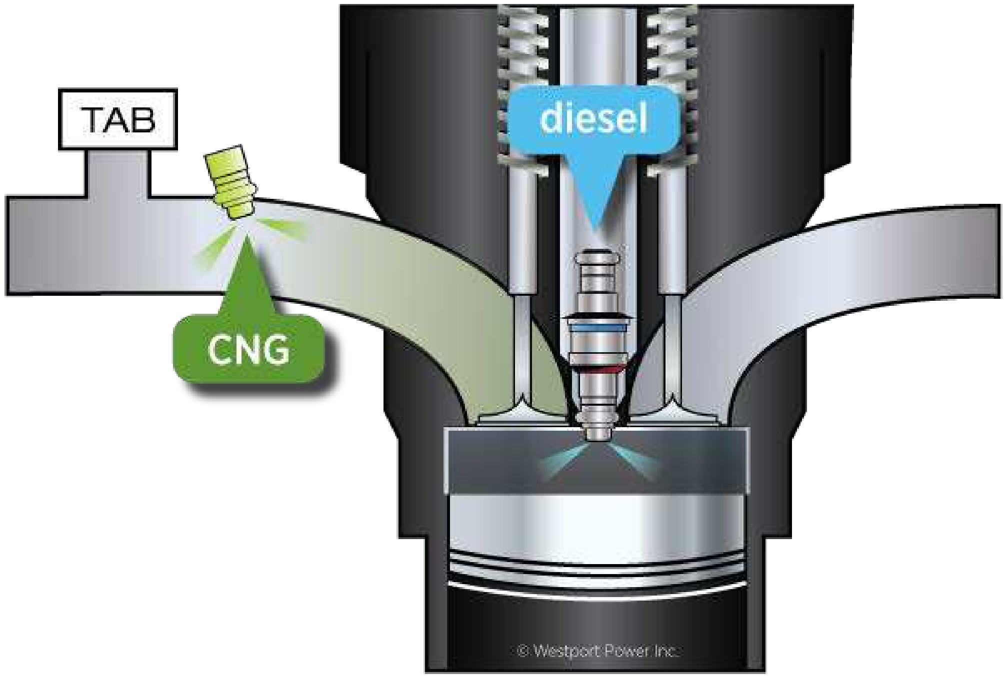


Figure 7: Example of dual fuel compression ignition engine (Cummins Westport [27])

Cummins Westport also offers compressed natural gas (CNG) powered vehicles using spark ignition engines, however, they are currently restricted to a maximum displacement of 11.9 litres which provides approximately 400 hp for use in regional haul tractors, vocational vehicles and buses to a maximum gross vehicle weight rating of 36,287 kg (80,000 lb). These have been described in more detail in Section 4.1.1.

DME has a cetane number of approximately 55 to 60 [1] [19] [26] [29] which, ironically, makes it a more suitable diesel cycle fuel than conventional pump diesel itself. Since the diesel cycle relies on auto-ignition rather than a spark induced ignition, the higher cetane number of DME results in a fuel that is more easily auto-ignited with a shorter ignition delay, a more complete combustion process and quieter operation when compared to conventional diesel.

The auto ignition temperature for DME is actually higher than that of diesel [23] at standard temperature and atmospheric pressure but the more important characteristic of auto-ignition temperature inside the cylinder is lower than those of other diesel fuels [19] [23] (508 K vs 523 K) which also helps to provide a more complete combustion process with less wasted fuel and less knocking, particularly at engine start up or when in-cylinder temperatures cool off. Tests performed by Park and Lee [19] demonstrated ignition advance for DME when compared to diesel of between 1.3 and 2.3 degrees of crank angle. The high cetane number and oxygen content improved the combustion and emissions characteristics such as early ignition and low PM and NO_x emissions (See Section 3.2.6.1 and Section 3.2.6.2).

3.2.3 Viscosity and Lubricity

DME in the liquid state has low viscosity and low lubricity, two properties which strongly affect the maximum achievable injection pressure in a fuel injection system [21]; viscosity allowing it to readily pass through narrow passages and the lack of lubricity can accelerate the wear of surfaces moving relative to each other such as the feed pump, the high pressure injection pump, and injector nozzles [19]. Due to the low viscosity and lubrication characteristics, fuel additives are mandatory to improve the fuel viscosity [19] to make DME a viable fuel for on road engines.

To demonstrate some of these issues, Bhide et al [30] blended DME with diesel fuel and demonstrated that the viscosity of the blended fuel dropped off rapidly as DME content rose, see Figure 8. Even 25% by weight of DME in a diesel blend will cause the viscosity to fall below the required levels, meaning that viscosity is a much greater limiting factor than miscibility if trying to combine diesel and DME. [31]

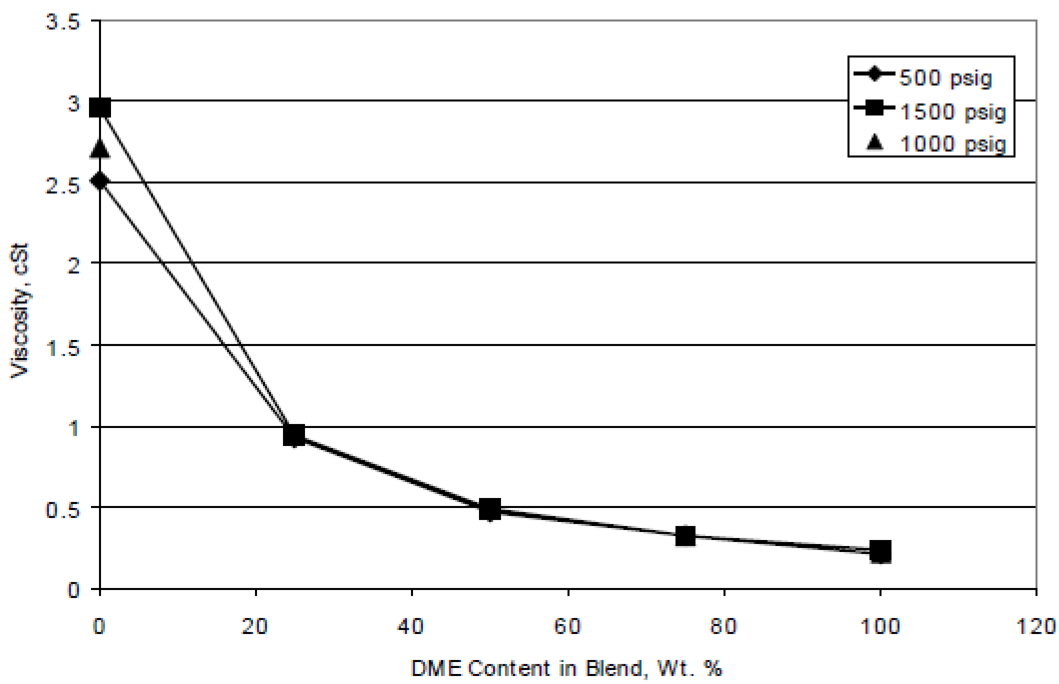


Figure 8: Viscosity vs. DME content in blended fuel [31]

A study performed by Sivebaek et al. [32] indicated that conventional diesel pumping equipment breaks down prematurely and significantly due to the use of DME. They investigated the effects of additives on DME viscosity using various fuels and additives, such as conventional diesel, biodiesel, soybean oil, Ethyl H4140, and Ethyl H580. They indicated that the use of additives to DME fuel cannot produce levels of the fuel viscosity or lubricity equal to those of conventional diesel fuel. [19] [32] Some laboratory tests using pure DME instead of diesel have caused pump failure in less than 30 minutes. Adding a small amount of lubrication significantly increased lubricity but still not to the point where it could be considered acceptable for the typical expected life of a highway tractor. They concluded that raising the lubricity of DME to acceptable levels may not be possible but changing the designs of the pumps to accept pure

DME could be a much more viable option, however, their research did not extend to pump redesign.

In a similar study, Nielsen and Sorenson [33] [34] added 900 ppm of Lubrizol to DME which greatly improved lubricity yet still resulted in premature and significant pump failure. It is clear from the research gathered that pure DME is incompatible with existing diesel fuel pumps and other hydro-machinery designed for conventional diesel.

The relationship between DME viscosity and pressure is shown in Figure 9 and shows a range of approximately 0.16 cSt to a high value of approximately 0.37 cSt, all of which is less than the ASTM D341 standard of between 1.39 to 4.2 cSt at 40 C. [19] (Note: kinematic viscosity is measured in centistokes, or cSt).

The low viscosity and back pressure of the fuel tank also affect the increase in injection duration [19]. Another study by Sivebaek et al. [35] concluded that viscosity and lubricity are very interrelated and that viscosity has a significant effect on the outcome of the wear tests. In addition, DME fuel has superior atomization performance compared to diesel fuel. The DME droplet size is considerably smaller than the diesel droplet size, which affects the formation and distribution of the fuel/air mixture [19].

McCandless et al. developed a highly specialized 275 bar DME plunger injection pump to be used with common rail injection architecture. Their system's moving parts were located away from the DME stream and therefore not affected by the DME's low lubricity [36] and different bulk modulus. When converting vehicles from conventional diesel to DME it will be important to consider new designs like this, rather than use existing equipment.

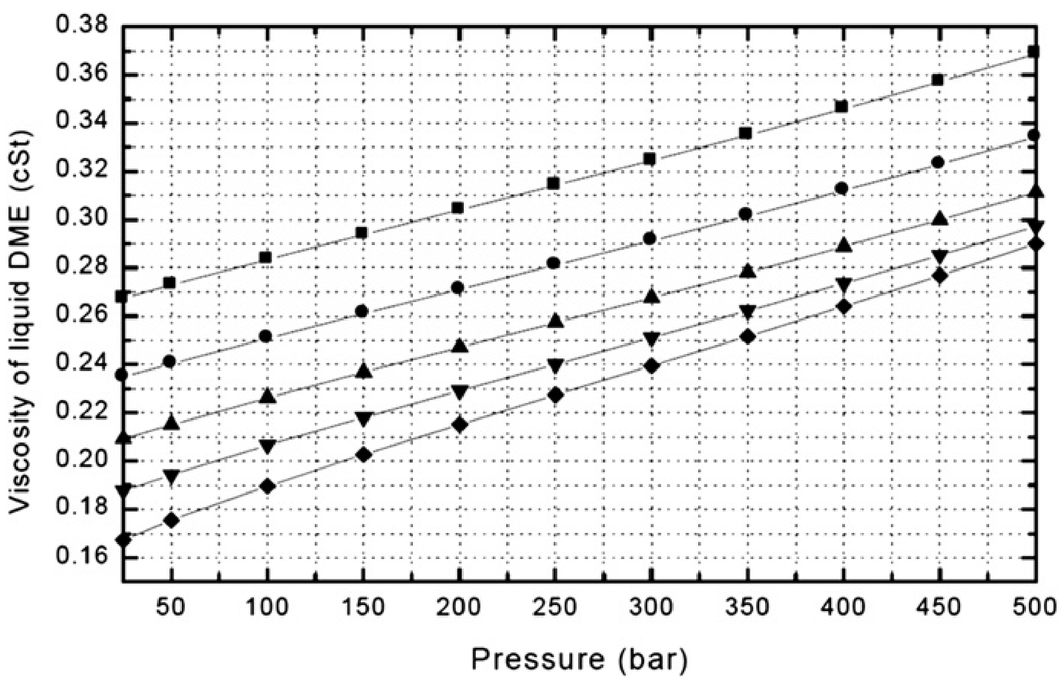


Figure 9: Viscosity of liquid DME at various pressures

In addition to its low lubricity and viscosity, DME adversely affects many types of plastics and rubbers and also dissolves nearly all known elastomers found in the fuel system. Retrofitting a vehicle to burn DME that is equipped with elastomers and certain plastics could result in very short service life of those components and possible fuel leaks or a reduction in working pressure. Laboratory tests have demonstrated that DME is compatible with Teflon® and Buna-N rubber. [37] In another test, the low viscosity of liquid DME caused a considerable leakage flow from the injection solenoids, which must be returned to the injection-pump inlet which could cause the fuel to heat up more than desired. Thus, a fuel cooler for cooling the recirculated liquid DME may need to be required in some DME fuel systems. [23]

The joint Volvo/Chemrec [1] study detailed the successful operation of DME powered vehicles for over 800,000 km but did not specifically state what type of fuel pump was used. They concluded that the lack of DME lubricity required maintenance intervals to be shortened in order to inspect and repair fuel pump equipment and to ensure the fleet continued to operate optimally. However, the authors noted that the performance of the fuel injection system far exceeded their expectations. Nonetheless, the research team are currently searching for methods to improve lubricity such that maintenance intervals can be lengthened to those currently used by diesel powered vehicles.

3.2.4 Heating Value and Energy Content

Lower heating value (LHV) and higher heating value (HHV) are indicators of available energy content, or energy density, of any fuel and can be expressed per unit of mass or by unit of volume. The measurement methods of LHV and HHV are outside the scope of this document but the higher the heating value, the more potential energy a fuel has per given volume, or mass. In general, the lower heating value (LHV) of DME (27.6 MJ/kg) is about 2/3 that of the LHV of conventional diesel fuel (42.5 MJ/kg). [19] Stated in other terms, one kilogram of DME has only 64.9% of the potential energy of a kilogram of pump diesel. Due to the differences in densities, one litre of DME has only about 53% of the potential energy of one litre of diesel (note that various publications give slightly different values for the heating value of DME but all of the values are approximately two thirds, by mass, for that of diesel fuel.). Therefore more DME (volume and/or mass) needs to be burned for every power stroke in a diesel engine in order to achieve the same power output, assuming all other factors are equal. This can be achieved by increasing the injection pressure, nozzle flow and/or injection duration, however, raising the injection pressure sufficiently is not possible in the foreseeable future, for reasons of viscosity and lubricity (Section 3.2.3). [21]

Park and Su [19] concluded that since DME fuel has lower density, and lower heating value compared with diesel fuel, more mass of injected fuel (about 48%) is needed to supply the same heat energy.

Table 6 shows the LHV, research octane number and density of various fuels, illustrating that DME has the lowest LHV (and HHV for that matter) of all conventional liquid and gaseous fuels. Some solid fuels have lower LHV and HHV values than DME but they have not been considered in this report due to their lack of use in the heavy haul trucking industry. Note that, in practice, nearly all of the values shown in Table 6 have ranges of values. Typical, or average, values have been shown in the table. [25] [38]

Table 6 – Heating values of various fuels (http://cta.ornl.gov/)

Product	Lower Heating Value (MJ/kg)/(MJ/litre)	Research Octane Number (RON)	Cetane Number	Approximate Density
Hydrogen	120.21/0.01	>125	NA	0.09 kg/m^3
Gasoline	43.44/32.39	90-100	NA	745 g/l
Low Sulfur Pump Diesel	42.50/36.04	15-25	40-50	848 g/l
Liquefied Petroleum Gas (LPG)	46.60/23.67	109	NA	508 g/l
Liquefied Natural Gas (LNG)	48.62/21.88	>127	<10	450 g/l
Compressed Natural Gas (CNG)	45.71/7.93	>127	<10	174 g/l
DME	27.60/18.38	35	55-60	666 g/l

In addition to the differences in LHV and HHV, DME has a higher combustion pressure and lower peak heat release value compared to pump diesel combustion [19]. The latent heat of DME is 467.13 kJ/kg at 20 °C, which is much higher than that of diesel fuel (300 kJ/kg). Since NO_x formation increases with in-cylinder temperatures, this can reduce NO_x emissions (See Section 3.2.6.2) due to the larger temperature drop of the mixture due to heat absorption during vaporization. [19]

3.2.5 **Compressibility**

The compressibility of a fluid is defined by its bulk modulus (K or B) and is typically measured in Pascals (Pa) or pounds per square inch (psi). Bulk modulus is essentially a measure of the ratio of how the volume of a fluid decreases relative to an applied pressure increase. The bulk modulus of any fuel (or additive) is an important factor when understanding how they behave before and during the injection process. The bulk modulus will determine how much a fuel changes in volume as it is compressed through the injectors and throughout the combustion process. For decades, engine manufacturers only had to deal with minor variations in bulk modulus amongst all of the various crude derived fuels. The advent of such fuels as bio-diesel and DME have forced engine manufacturers to carefully consider how the bulk modulus of the fuels will affect the performance, reliability and maintainability of the engines. [39] For instance, many engines that are set up to run optimally with bio-diesel are tuned with slight engine timing advance, when compared to those engines burning conventional diesel. However, the use of common rail diesel fuel injection systems has greatly reduced the influence of bulk modulus on the fuel injectors since the fuel is maintained at constant pressure in the rail and then released into the cylinders as a timed event via an electro-mechanical pulse, rather than by hydraulic action. However, the effects on upstream devices such as the fuel pump remain, therefore it is not practical to use existing diesel fuel pumps with DME.

Tests have demonstrated that the bulk modulus of DME is approximately 1/3 that of conventional diesel. [19] Research by Park and Lee demonstrated that due to DME's low elastic modulus, the compressibility of DME is higher than that of diesel fuel, which means that the compression energy in the DME fuel pump is greater than that in the diesel fuel pump. [19] In the case of a final compression pressure of 25 MPa at 323 K, the compression energy for DME fuel was 3.2 times greater than that of dodecane in a closed system. Lapuerta et al. [39] concluded that it was possible to experimentally test various fuels, determine their bulk modulus and then derive correction factors for each fuel to optimize the injection timing and pump pressures within the engine. However, their research was focused on bio fuels not DME but it is suspected that their methods could be transferred to DME.

Teng at al. [23] studied the fuel injection properties of DME. Their overall conclusion was that one of the more significant challenges in using DME as a diesel-fuel substitute is the modification, tuning and management of engine fuel delivery system. They noted that for a conventional diesel fuel, variations in fuel pressure will induce very limited changes in density and the speed of sound of the fuel in the injection line. However, because DME is highly compressible (i.e. different bulk modulus from diesel), fluctuations in density and the speed of sound for fuel in the injection line between two injections may be significant and thus they must be taken into consideration in the fuel management mapping. This affects the injection delay because the front of the injection-pressure wave travels from the injection pump (or the injection solenoid) to the orifices of the injector at the speed of sound. [23] All of these factors must be considered when tuning a DME powered vehicle.

3.2.6 **Tailpipe Emissions**

DME's influence on the more commonly monitored vehicle tailpipe emissions (Section 2) has been described in this Section. The emissions produced in the production, refining, delivery and disposal of DME have not been considered. A separate 'well to wheel' analysis would be required to fully understand and quantify those effects and it is likely that each of the separate DME production methods would yield different wheel to well results, making such a study a non-trivial task.

3.2.6.1 Particulate Matter Emissions

As discussed in Section 2, one of the principal disadvantages of burning conventional diesel is the formation of particulate matter (PM) emissions. This visible soot is a direct result of the carbon-to-carbon bond found in diesel fuel and can cause significant blackening of buildings adjacent to roads that are heavily travelled by diesel powered vehicles. This soot is not only damaging to human health and infrastructure (Section 2) but is visually unappealing to pedestrians outside of the vehicle(s), resulting in a potentially negative public perception of diesel powered fleet vehicles such as city buses or delivery trucks. The United States EPA and Environment Canada have made significant progress in reducing the levels of PM being released by diesel engines, however, this has come with penalties such as increased engine and vehicle acquisition costs, increased vehicle tare weight (and corresponding decrease in available payload) and increased maintenance requirements/costs. Additionally, some of the devices used to decrease PM cause the vehicle's engine to burn slightly more fuel, thus increasing CO_2 emissions slightly. The absence of a carbon-to-carbon direct bond [19] in DME results in a combustion process that is nearly soot (PM) free meaning that PM levels can be reduced to near zero levels and fully compliant with the EPA's Tier 4 (off-road) and pollutant (on-road) regulations without the need for diesel particulate filters (DPF) or traps. The impact to trucking in terms of space claim, cost and weight will be discussed in much greater detail in Section 6.7.

In one study, Salsing et al. describe DME as having excellent combustion characteristics [21] and generates no soot particles even under poor combustion conditions, and low amounts of unburned hydrocarbons with relatively uncomplicated composition. From the research that was reviewed it became clear that reduced particulate matter (PM) is one of the greatest potential benefits of DME. As described in Section 3.2.1, the lack of carbon-to-carbon bond makes DME an inherently soot free fuel and many papers and studies consistently demonstrated a dramatic decrease in PM levels (as much as two orders of magnitude lower) when compared to pump diesel.

A variety of in depth studies were reviewed, most notably the joint venture between Volvo and Chemrec, described in Section 3.1. The two year BioDME study [1] concluded with emissions testing for the highest mileage vehicle of the ten vehicle fleet (183,000 km). The results were consistent with the theory in that the tailpipe PM emissions from the 60t loaded vehicle and the unloaded 20t vehicle averaged 0 g/kWh when compared to the (then) Euro V specification of 0.02 g/kWh. The test results are also well below the current North American standards of 0.014 g/kWh (shown in Table 2).

A recent test performed by the Oak Ridge National Laboratory [22] in conjunction with Volvo Trucks and Penn State University showed particulate matter emissions that were near zero. The tests involved a Euro V compliant tractor with a 13.0 L engine making 450 hp using a common rail type fuel injection system. The vehicle did not contain selective catalytic reduction (SCR) or a diesel particulate filter (DPF) or a trap of any kind. A diesel oxidation catalyst (DOC) was the only after treatment device on the vehicle. For comparison sake, a conventional vehicle using SCR, a DOC and a DPF was also tested. The tests revealed an average PM level of 0.004 g/mi for the 60 mph drive cycle and an even lower value of 0.001 g/mi for the Heavy Heavy-Duty Diesel Truck (HHDDT) drive cycle for the DME vehicle (reductions of 36 times and 145 times respectively). Test result data could not be found for the conventional vehicle, however, according to the EPA, the average PM level for heavy duty vehicles is approximately 0.202 g/mi but this is assumed to be a gross average and individual results will vary. Regardless of the exact baseline value, it is clear that the use of DME can reduce PM emissions by as much as 50 to 200 times that of conventional diesel, due to the lack of carbon-to-carbon bond. When considering the more important unit of grams per horsepower hour, the Oak Ridge/Volvo tests achieved a combined value of 0.0008 g/hp-hr. The current on-road EPA regulations set this value at 0.014 g/kWh (0.01 g/bhp-hr) meaning that the DME powered vehicle without add on devices had PM levels that were 12.5 lower than the current EPA standard which can generally only be achieved in diesel engines with SCR and DPF/traps.

That being said, it is also important to classify the particle size of PM emissions since the human body can ingest different particle sizes differently. In 1987, the EPA replaced the earlier Total Suspended Particulate (TSP) air quality standard with what is known as the PM-10 standard. The new standard focuses on smaller particles that are likely responsible for adverse health effects because of their ability to reach the lower regions of the respiratory tract. The PM-10 standard includes particles with a diameter of 10 micrometers or less. Major concerns for human health from exposure to PM-10 are shown in Table 1. New scientific studies suggest that fine particles (smaller than 2.5 micrometers in diameter) may cause serious adverse health effects. As a result, the EPA is considering setting a new standard for PM-2.5. In addition, EPA is reviewing whether revisions to the current PM-10 standards are warranted. According to the British Department for the Environment, Food and Rural Affairs, airborne particles are usually considered as belonging to three size modes. The smallest is the nucleation mode, which includes particles newly formed through source condensation processes or through atmospheric chemical reactions. These particles grow – through coagulation and vapour condensation – into the accumulation mode, where they may have a long atmospheric lifetime. Particles with a diameter greater than ~1 µm, are referred to as the coarse mode; they are typically generated through mechanical processes such as quarrying or sea spray formation by breaking waves. [40]

Kwak et al. studied not only the levels of PM emitted from buses using various fuels but also attempted to quantify the size distribution of the particles. The test vehicles were minvans/minibuses burning CNG, LPG, diesel and DME at various road speeds, including idle.

The gaseous pollutants and particles were all measured using a mobile emissions laboratory [24]. It is interesting to note that although their tests revealed very low PM emissions when considering the accumulation mode, it also revealed that DME has the highest percentage of nano-particles (based on number concentrations) compared to CNG, LPG and diesel. Their overall conclusion was that nano particle number concentrations for DME were as high as 99% during driving cycles. But this is still 99% of a value that was 48 times less than the accumulation mode numbers for conventional diesel PM emissions they tested. These numbers are in keeping with the theory about DME PM emissions, as presented above. In a similar series of tests, Salsing and Denbratt [41] concluded that the total number of particles from their emissions tests were three orders of magnitude lower than the number for a clean diesel engine. However, they noted that the particle number peak was below the soot size range and was comparable to diesel in that range.

As expected, these test results confirmed that a heavy duty vehicle can pass both the EPA off-road Tier 4 regulations and on-road pollutant regulations for particulate matter (PM) without the use of traps or filters. Therefore, it is fair to assume that any new vehicle powered by DME could be delivered without a DPF and any vehicle that has been converted to run on DME could operate with the DPF either bypassed or removed from the vehicle entirely. This will reduce the tare weight of the vehicle by approximately 50 kg and will eliminate DPF related preventive maintenance activity as well as the need to monitor emissions related fault codes (both critical and nuisance) seen at the driver's station.

More study will be required to determine the quantity and effects of the nano PM particles that are being created by a DME powered engine, not only in terms of human health (Section 2) but in terms of engine wear (See Section 6.6). Nearly all of the PM produced by a DME powered engine are nano sized, however, it is not clear from the research if the absolute volume and count of PM particles could pose a risk to human health as a result of tailpipe emissions from Canadian vehicles.

3.2.6.2 NO_x Emissions

Nitrogen by itself is harmless. However, the oxidization to NO_2 can irritate lung tissue. NO_2 also combine with water to form nitric acid which can damage trees and other plants. Nitrogen oxides have also been categorized as a precursor to smog forming ozone. As with the other emissions, it will be important to determine how burning DME could affect the production of NO_x, given how much effort has been expended to reduce NO_x throughout the industry. Many studies have included the measurement of NO_x, however, unlike PM measurements, the NO_x results seemed rather varied. The main cause of elevated NO_x is high in-cylinder temperatures. Therefore there are two principal ways in which tailpipe NO_x can be reduced. The first method involves reducing in cylinder temperatures via exhaust gas recirculation (Section 2.2.2) and the second method is by treating the exhaust downstream using selective catalytic reduction (Section 2.2.1). Most diesel engine manufacturers have elected to drastically reduce NO_x formation via SCR and abandoned the notion of massive EGR at the engine.

Some research has shown that, for DME, a low boiling point results in a rapid evaporation of the liquid phase DME in the cylinder. This decreases the gas pressure in the engine and causes a temperature drop during the combustion process [19] which can aid in the reduction of NO_x. However, tests performed by Park and Lee [19] also revealed that DME NO_x emissions can be higher than those of a diesel engine since the faster ignition of the DME fuel mixture increased the charge temperature in the cylinder, NO_x formation was higher during the combustion process for DME fuel than for diesel fuel [19]. Figure 10 illustrates that NO_x was found to be higher at all crank angles for DME when compared to diesel. However, the slightly higher NO_x emissions during DME combustion can be reduced by the application of EGR [19] which reduces in cylinder temperatures enough to lower the NO_x values to diesel levels albeit at the cost of possibly increasing CO and/or THC emissions since the lowered temperature cannot burn off the carbon content as quickly (Section 3.2.6.3). However, unlike diesel fuel, there is no trade off with increased PM emission since PM emissions are essentially zero in a DME fueled engine. [19]

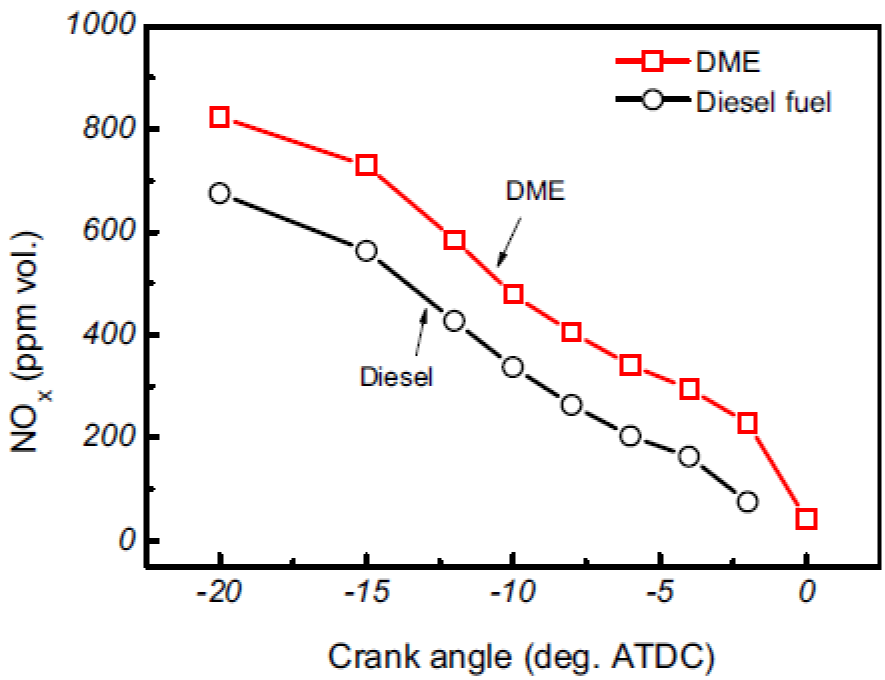


Figure 10: NO_x emissions for DME and diesel fuel with constant energy input [59]. [19]

Park and Lee also experimented with fuel injection timing. With pilot injection timing of 10 deg before top dead centre (BTDC), NO_x emission was reduced by about 76.1% compared to diesel combustion [19]. As the pilot injection timing advanced to 40 deg BTDC with the same main injection timing, a 95% reduction in NO_x emission was achieved [19]. The two stage combustion of DME induced the low NO_x emission by the formation of relatively low local equivalence ratio before the ignition and combustion process. [19] Tests conducted by Kwak et al. resulted in a 40.1% reduction in HC and 48.2% reduction in NO_x relative to conventional diesel [24].

The two year Volvo/Chemrec DME study [1] included ten vehicles, all of which did not have SCR installed [42], but rather relied on cooled EGR to manage the NO_x reduction. The tests concluded with emissions testing for the highest mileage vehicle of the ten vehicle fleet (183,000 km). The loaded 60t vehicle produced average NO_x emissions of 1.72 g/kWh whereas the unloaded 20t vehicle produced 1.66 g/kWh. Both of these values were below the (then) Euro V specification of 2.0 g/kWh, without the use of SCR, but are well above the current Euro VI and EPA/EC on road standards shown in Table 2.

Kim et al. [43] [44] demonstrated that ultra-low NO_x emission can be achieved by creating multiple fuel injections in a partially premixed charge compression ignition engine (PPCCI) in a single-cylinder diesel engine. In their experiment, DME was injected very early in the cycle (beyond 60 BTDC) producing negligible NO_x emissions because DME burned with the premixed charge combustion ignition (PCCI), and a second fuel injection at a later timing produced a negligibly low level of NO_x emissions with extra power.

Tsuchiya and Sato [45] created a DME powered 20 ton freight truck and varied the levels of EGR and engine load from moderate to high and noted a very strong linear relationship between increasing levels of EGR and decreasing levels of NO_x for all engine loads. As seen in Figure 11 NO_x levels could be reduced by as much as 80% at some combinations of load and EGR. However, their studies did reveal that fuel consumpti0on did increase for most test cases (-2% to +10%) as a result of increasing levels of EGR, as seen in Figure 12.

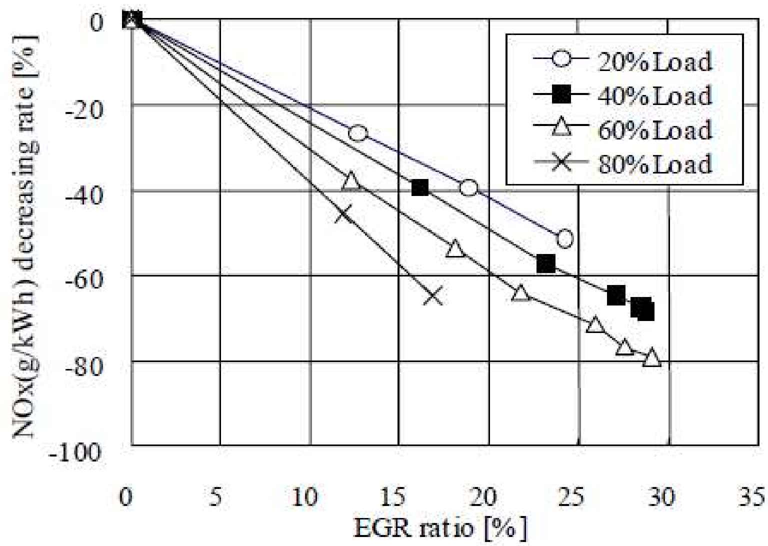


Figure 11: NO_x emissions for DME at various EGR and engine load levels

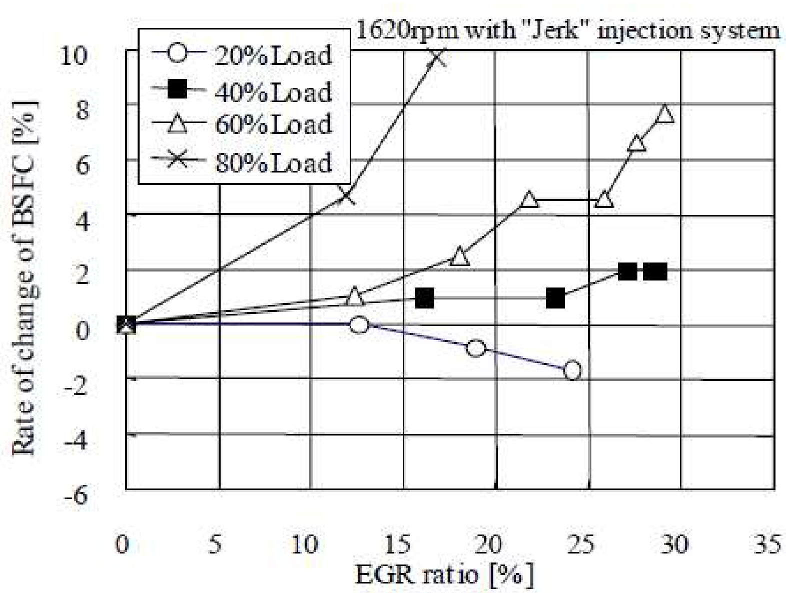


Figure 12: Brake specific fuel consumption for varying levels of EGR

Similarly to what was described in Section 3.2.6.1, the joint Penn State, Volvo, Oak Ridge testing [22] also measured NO_x levels for their DME powered test tractor. The tests revealed an average NO_x measurement of 3.92 g/mi for the 60 mph constant speed tests and 4.31 g/mi for the HHDDT cycle. The value of g/hp-hr was then calculated for the 60 mph cycle to be 0.83 g/hp-hr which is more than four times higher than the 2010 EPA regulation of 0.20 g/hp-hr (0.27 g/kWh shown in Table 2). Therefore the significant reductions in PM described in Section 3.2.6.1 were offset by an increase in NO_x. The authors theorized that increasing EGR on the engine could reduce the NO_x emission to below the 2010 regulatory levels without adversely affecting vehicle weight but the effects on fuel consumption would also have to be investigated due to the lower in cylinder temperatures and possible combustion phasing required to achieve these NO_x reductions.

Yoon et al [46] reported performing a series of tests aimed at quantifying emissions on a small direct injection diesel engine powered by DME. The intent of their tests was to determine if there was a relationship between varying levels of EGR and emissions as NO_x, HC and CO (Section 3.2.6.3). They varied EGR from 0% to 30% to 50% while also varying injection timing from 40° BTDC to 0° (top dead centre). As expected, the levels of NO_x decreased significantly with increased EGR rates but this tended to increased CO and HC levels when timing was advanced above 25°. The PM particle volume and particle count also increased as EGR rates increased, however, these counts were slightly reduced as timing was increased. Figure 13 [46] illustrates the dramatic decrease in NO_x emissions that can be achieved via high EGR and careful selection of injection timing.

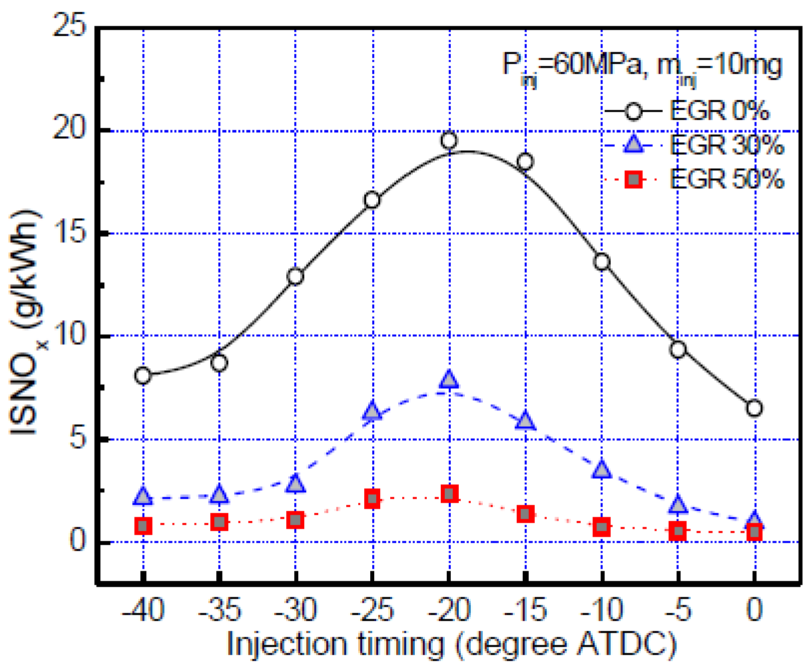


Figure 13: NO_x emissions for DME with variable EGR rate [46]

It is clear that NO_x levels will create a difficult design optimization dilemma for engineers and fuel injection tuners who wish to use DME as a fuel in diesel engines. The near zero levels of PM could result in SCR removal while in cylinder temperatures are reduced to reduce NO_x

levels via conventional EGR. However, this may have other adverse effects on engine wear, fuel consumption and hydrocarbon levels. Alternately, if just the DPF and traps are removed as a result of the low PM levels but SCR remains on the vehicle to reduce NO_x levels, the vehicle will retain much of the newer devices that are currently reducing space claim and increasing capital cost and maintenance activity. If SCR is to be removed from vehicles, much study will have to be performed to adequately determine how much additional EGR [47] or modified/multiple injection strategies [48] will be required to reduce NO_x to acceptable levels in a DME powered vehicle and to quantify the secondary effects, particularly fuel consumption and engine wear.

3.2.6.3 Hydrocarbon and Carbon Monoxide Emissions

Two of the regulated emissions monitored by the EPA are hydrocarbon (HC)/ total hydrocarbon (THC) and Carbon Monoxide (CO). Hydrocarbon can be emitted in many forms, but the hydrocarbon found in DME emissions is generally of the form CH_3 whereas the form found in diesel emissions is $CH_{1.86}$.

In 2004, Teng [23] et al. demonstrated that the DME combustion process produced less HC than a similarly equipped engine burning conventional diesel. Park and Lee [19] stated that HC emissions from a DME-fueled engine are usually lower than or equal to that of a diesel engine because the evaporating characteristics of DME contributed to improved mixing characteristics of fuel and air. Therefore, the unburned mixture remaining during the combustion period would be less than that remaining with diesel, thus reducing HC formation. Their figures are shown in Figure 14 and clearly show that HC and CO are both lower for all crank angles when burning DME compared to diesel.

In another study, DME combustion produced less unburned hydrocarbons than that from diesel-fuel combustion and, as a result, an engine fueled with DME generally had a lower specific HC emission than that when fueled with diesel fuel and operated at the same condition. [23]

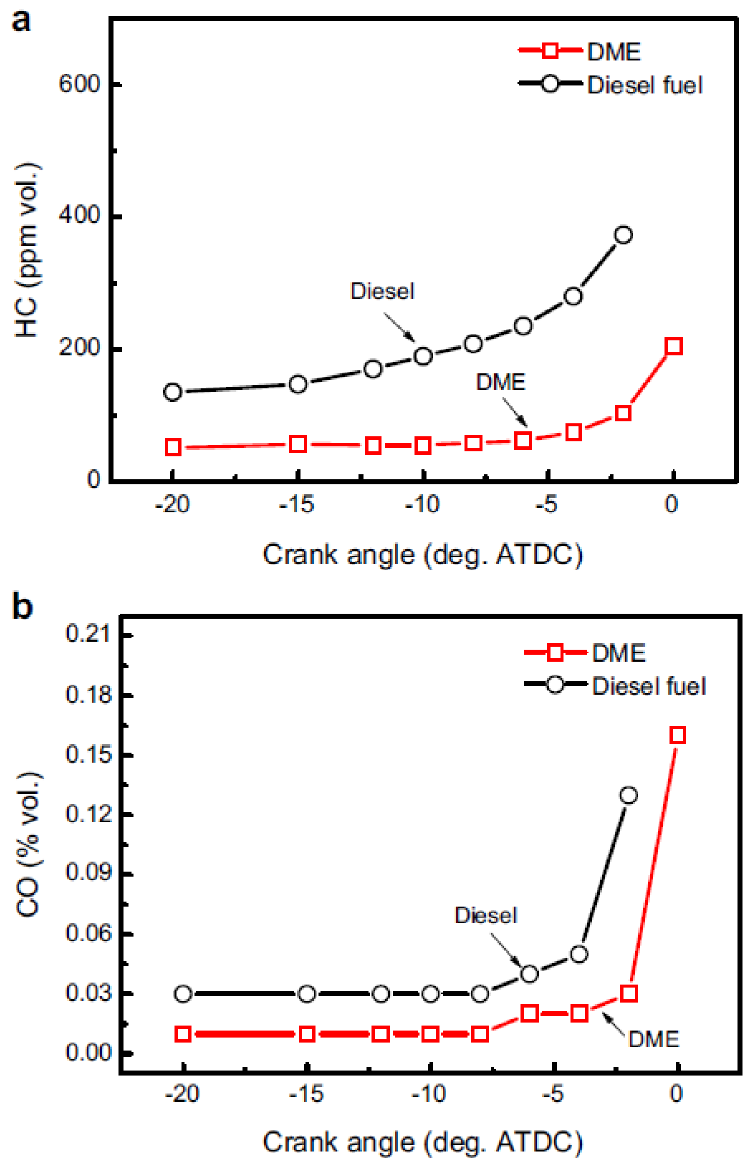


Figure 14: HC and CO for DME and diesel, constant energy, (a) HC; (b) CO [59] [19]

Park and Lee also noted that the amount of fuel-rich mixture would be small during the combustion process of the DME-fueled engine since DME has good mixing characteristics. Therefore, CO emission is reduced [19]. Additionally, the higher oxygen content, faster ignition and high volatility in DME tends to supress CO production when compared to diesel.

Results from the Penn State, Volvo testing showed mixed results. The CO measurements for the 60 mph constant speed test revealed CO values of 0 g/mi., however, for the HHDDT cycle, the average emission was much higher at 1.16 g/mi.

The tests described in the previous section, performed by Yoon et al [1200], also resulted in data relating to HC and CO formation. Their work revealed that injection timing is a far more significant factor when considering the formation of HC than the level of EGR. Although there is some EGR effect at very high injection advance timings (see Figure 15) where increasing EGR increased HC levels significantly. Similar trends can be seen for CO formation (Figure 16), where a combination of high injection advance and high EGR resulted in much higher CO levels (some as high as 60 times more than no EGR and low advance timing).

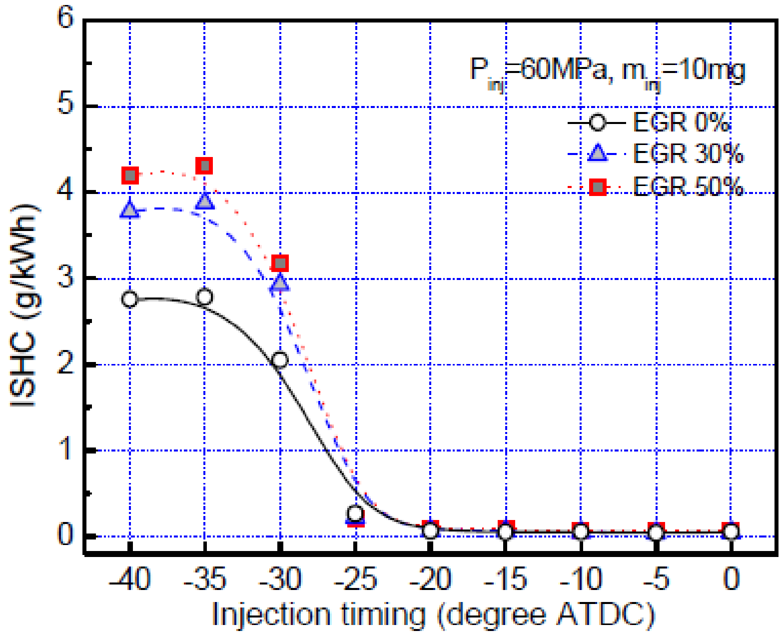


Figure 15: Effect of EGR on HC formation [1200]

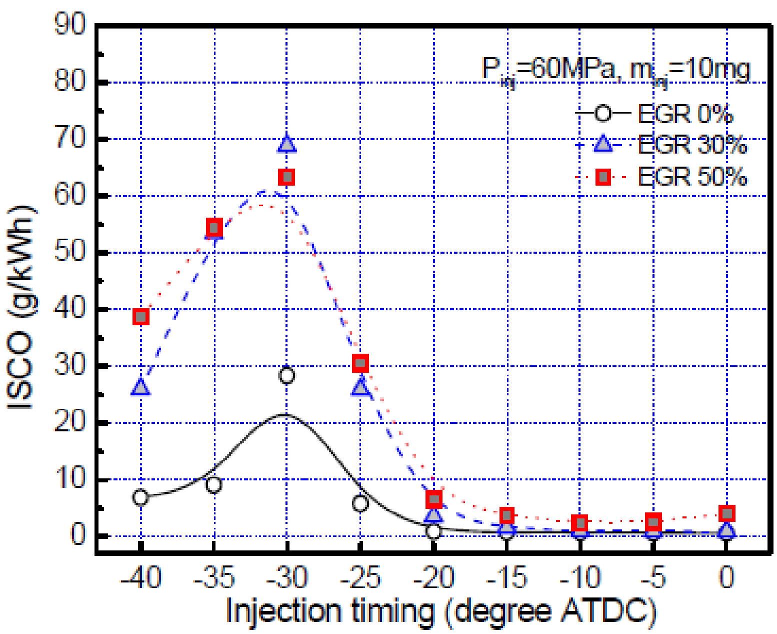


Figure 16: Effect of EGR on CO formation [1200]

The two year Volvo/Chemrec DME study [1] involved vehicles without SCR but with diesel oxidation catalysts on board. The tests concluded with emissions testing for the highest mileage vehicle of the ten vehicle fleet (183,000 km). The loaded 60t vehicle produced average HC emissions of 0.31 g/kWh whereas the unloaded 20t vehicle produced 0.25 g/kWh. Both of these values were below the (then) Euro V specification of 0.40 g/kWh. Carbon monoxide levels were found to be 1.82 g/kWh and 2.34 g/kWh respectively, which are both lower than the (then) Euro V specification of 3.0 g/kWh.

However, the use of EGR to offset increases in NO_x could result in lowered in-cylinder temperatures that could result in higher levels of THC. These effects would require additional tests to confirm using a variable or tunable EGR to balance off the NO_x and THC emissions or the use of Diesel Oxydation Catalysts (DOC see Section 2.2.3) to reduce HC and CO if massive EGR is requested.

Much of the scientific work has confirmed that HC and CO levels can remain very low provided that injection timing and EGR levels are taken into consideration. Failure to correctly map injection timing and EGR rates can result in extremely high levels of CO (60+ g/kWh) and HC (4+ g/kwH), both of which exceed EC's current regulatory levels.

3.2.6.4 Carbon Dioxide (CO_2) Emissions

As discussed in Section 2, CO_2 is one of the few emissions that cannot be reduced by the addition of engine or downstream devices. Until recently, engine manufacturers have primarily focussed on reducing PM, NO_x, HC and CO via the use of add on devices, but CO_2 emissions have remained largely unchanged throughout this process. The recent GHG reduction targets are causing OEMs to also focus on CO_2 reduction strategies (i.e. fuel consumption) at both the engine and vehicle levels. Burning less fuel or burning different grades of fuel are the only practical ways to reduce CO_2 emissions therefore it will be of great interest to determine if alternative fuels, such as DME, could be used to reduce CO_2 levels to match the values found in the GHG regulations without altering, say, the power output of the engine or the aerodynamics of a vehicle.

Advances in aerodynamics and rolling resistance do not have any effect on fuel consumption when a vehicle is idling. Given the volume of fuel that is burned every year for on-road transport idling, it will be important to understand the role that DME could play in reducing this carbon footprint. Calculations performed by Argonne labs in the US revealed that over 8 billion litres of diesel are burned every year for idling alone if all forms of idling are considered. [15]

Teng et al [23] performed a complete thermodynamic study of DME in 2004. One of the aspects of the study focussed on CO_2 and water emissions where 1.0 kg of conventional diesel was burned and the levels of CO_2 and H_2O were monitored. Then, 1.49 kg of DME (i.e. the equivalent amount of DME compared to diesel based on lower heating value, see Section 3.2.4 of this report) was burned as a comparison. The results are shown in Table 7 and illustrate that DME produces 4.5% less exhaust, by mass, than diesel, 9.5% less CO_2 than diesel but approximately 45% more pure water (H_2O).

Table 7 – CO_2 emissions for DME and diesel [23]

Fuel	Mass	Exhaust	CO_2	H_2O	CO_2 (wt%)	H_2O (wt%)
Diesel	1.00 kg	15.60 kg	3.17 kg	1.21 kg	20.37	7.76
DME	1.49 kg	14.90 kg	2.87 kg	1.76 kg	19.26	11.81

The results of this study demonstrated that for every 43 MJ of fuel energy, DME produced 0.70 kg less total exhaust, 0.30 kg less CO_2, and 0.55 kg more H_2O than diesel fuel. The specific CO_2 emissions for DME and diesel fuel are, respectively, 66.74 g_{CO2}/MJ and 73.72 g_{CO2}/MJ, indicating that the CO_2 emissions of DME were approximately 9.5% less than from conventional diesel fuel. [23]

The calculations shown in Table 3 were repeated but with the CO_2 emissions for DME inserted in place of those for diesel (i.e. 0.30 kg less CO_2 per equivalent fuel mass). Of the 128 DME cell entries, 76 were compliant for 2014 and beyond (63 for diesel), five were compliant after 2014 but not after 2017 (three for diesel) and 47 were not compliant at all (62 for diesel). The Table shows that 15 more pairings of power and fuel consumption are below the emissions standards set out by Environment Canada meaning that engines that are currently slightly over the new federal standards (637 g/kWh 2014 and 617 g/kWh 2017) could be made to pass if they burned DME in place of diesel. However, this of course assumes that the fuel consumption for the DME powered vehicle was the same as the diesel powered vehicle, which may or may not be the case and would need to be tested in accordance with federal test procedures to confirm. Although hypothetical, the tables are shown as an example of how CO_2 can be reduced by using DME. The relative values and comparisons between the two fuels portray an accurate reflection of these reductions, even if the numerical emission test values shown in the table are somewhat artificial. Once again, it must be stated that these are reflective of tailpipe emissions and not "well to wheel" analysis.

Table 8 – CO_2 emissions for various power and fuel consumption pairings, 105 km/h

CO_2 emissions (g/kWh) using pump diesel									
	Power	**Engine Power**							
	hp	**375**	**400**	**425**	**450**	**475**	**500**	**525**	**550**
	kW	**280**	**299**	**317**	**336**	**354**	**373**	**391**	**410**
Average Fuel Consumption (l/100 km)	**40**	354.88	332.70	313.13	295.73	280.17	266.16	253.49	241.96
	45	399.24	374.29	352.27	332.70	315.19	299.43	285.17	272.21
	50	443.60	415.87	391.41	369.67	350.21	332.70	316.86	302.45
	55	487.96	457.46	430.55	406.63	385.23	365.97	348.54	332.70
	60	532.32	499.05	469.69	443.60	420.25	399.24	380.23	362.95
	65	576.68	540.64	508.84	480.57	455.27	432.51	411.91	393.19
	70	621.04	582.22	547.98	517.53	490.29	465.78	443.60	423.44
	75	665.40	623.81	587.12	554.50	525.32	499.05	475.29	453.68
	80	709.76	665.40	626.26	591.47	560.34	532.32	506.97	483.93
	85	754.12	706.99	665.40	628.43	595.36	565.59	538.66	514.17
	90	798.48	748.57	704.54	665.40	630.38	598.86	570.34	544.42
	100	887.20	831.75	782.82	739.33	700.42	665.40	633.71	604.91
	105	931.56	873.34	821.96	776.30	735.44	698.67	665.40	635.15
	110	975.92	914.92	861.11	813.27	770.46	731.94	697.09	665.40
	115	1020.28	956.51	900.25	850.23	805.48	765.21	728.77	695.65
	120	1064.64	998.10	939.39	887.20	840.51	798.48	760.46	725.89

3.2.6.5 Other Emissions

Most of the notable diesel emissions have been covered in the previous sections, however, there are other emissions of interest monitored by the EPA. Park and Lee [19] discussed the formation of some of the more common Oxygen based emissions (NMOG Section 3.2.6.5) and concluded that compounds such as formaldehyde (HCHO), acetaldehyde (CH_3CHO), and formic acid (HCOOH) were all found to be higher for DME than for diesel. This is due to the high Oxygen content and additives in DME whereas diesel is Oxygen-free. Gray and Webster [49] noted that formaldehyde emissions were 382% higher for DME when compared to diesel, although they also noted that diesel formaldehyde emissions are normally extremely low. Other researchers also noted that the formaldehyde can be reduced to negligible levels by the use of a diesel oxidation catalyst [19] whereas the catalyst had no effect on the reduction of acetaldehyde. They concluded that if, and when, DME is used as a mass produced on-road fuel, careful attention will need to be paid to the lubricity additives that are mixed with DME as they can adversely affect the generation of these Oxygen based compounds and the reduction in PM could be offset by an increase in other toxins. NRC-AST could not find significant data to substantiate or refute these claims therefore further work in this area may be warranted in order to fully quantify these emissions and their potential to affect human health and infrastructure.

3.2.7 **Interdependence of All Emission Reduction Components**

As demonstrated in Section 3.2.6.1, PM levels are sufficiently low with DME fueled vehicles that in-cylinder temperatures can be lowered which would result in a decrease in NO_x levels which could, in turn, reduce the need (either partially or fully) for SCR. Some level of exhaust gas recirculation could then be used for the remainder of the required NO_x reductions. This could potentially free up space claim behind the cab and under the vehicle that can be better used by the operator, and returns the appearance, function and weight distribution of the tractor to pre-2010 specifications (See Section 6.7 for more details regarding weight distribution). In addition, the removal of SCR would reduce the vehicle's dependence on the urea based diesel exhaust fluid thus relieving the operators of this financial burden as well as the need to ensure the fluid is available in remote locations. However, lowering in-cylinder temperatures could increase emissions of hydrocarbons which would potentially require the use of a diesel oxidation catalyst (DOC) to return these levels to below the required regulations. The relationships between EGR, SCR and DOCs are complicated and more study would be required to determine if SCR could be removed without any detrimental effects to the fuel consumption, HC, CO and NO_x levels of the vehicle due to the lowered in-cylinder temperatures. One unfortunate circular argument is as follows: removing SCR would be beneficial for vehicles that travel in remote locations where a steady supply of urea mixture is either difficult to locate or is cost prohibitive. However, such a remote location would likely have even less of an infrastructure for DME, unless a dedicated filling station was created such as the one discussed in the Volvo study. [1]

One emissions aspect is clear: despite the ambiguity regarding the removal of SCR, levels of PM are so low that the use of DME would most certainly allow users to remove DPFs from their vehicles.

4 COMPARISON OF DME TO OTHER ALTERNATIVE FUELS

The physical and chemical characteristics of DME were compared primarily to conventional diesel in Section 3. Although not nearly as prevalent, compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LPG) can also be used as on-road fuels and are therefore worthy of comparison against the properties of DME. In addition to the physical characteristics of the fuels, factors such as supply chain, storage, costs and safety risks have also been included. The chemical properties of the fuels will be discussed in this Section whereas vehicle and transportation sector specific comparisons have been addressed elsewhere.

4.1 Natural Gas

Natural gas is primarily a methane based fossil fuel that is derived from plant and animal matter that has been compressed for thousands of years between deep layers of the earth. Unlike DME, conventional natural gas cannot be produced within a human lifetime therefore it is considered to be a non-renewable resource. Bio-mass produced gas is considered renewable but currently represents a minute portion of the global supply of delivered natural gas. The two most popular forms used for transportation, CNG and LNG, have been described separately below, however, it is important to note that the engines used to burn LNG and CNG are identical; it is the means of transportation, handling and storage of the fuels that differ between LNG and CNG. Fleet operators who choose natural gas must decide what aspects are critical to their specific operations before deciding whether they would be better suited to LNG or CNG operations. These include range, proximity to fueling stations, vehicle weight and duty cycle to name a few.

In general, natural gas is touted to have a lower CO_2 footprint, a lower price and improved ombustion efficiency when compared to conventional diesel. [28] Figure 17 illustrates the energy density (Section 3.2.4) of many transportation fuels, measured in the US units of thousands of BTU per cubic foot. The exact numerical values and units are not important but the relative energy densities of alternative fuels when compared to diesel are important to note when calculating tank size differences, vehicle range and engine power (or power de-rating). For this reason, the concept of a 'diesel gallon equivalent' or DGE has been developed as a unit-less measure of a fuel's relative power compared to diesel, on a volumetric basis. For example, ~3.98 units of CNG are required to achieve the same amount of energy as 1 unit of diesel. Studying Figure 17 reveals DGEs for LNG, CNG, DME and other selected alternate fuels shown in Table 9. The higher the number, the more fuel that is required to achieve the same power output as diesel.

Table 9 – Diesel gallon equivalent of various fuels

Fuel	Diesel Gallon Equivalent (DGE)
Diesel	1.00
Gasoline	1.15
E85	1.53
Propane/LPG	1.55
LNG	1.56
Ethanol	1.67
DME	1.88
Methanol	2.19
CNG	3.98
Hydrogen	15.56

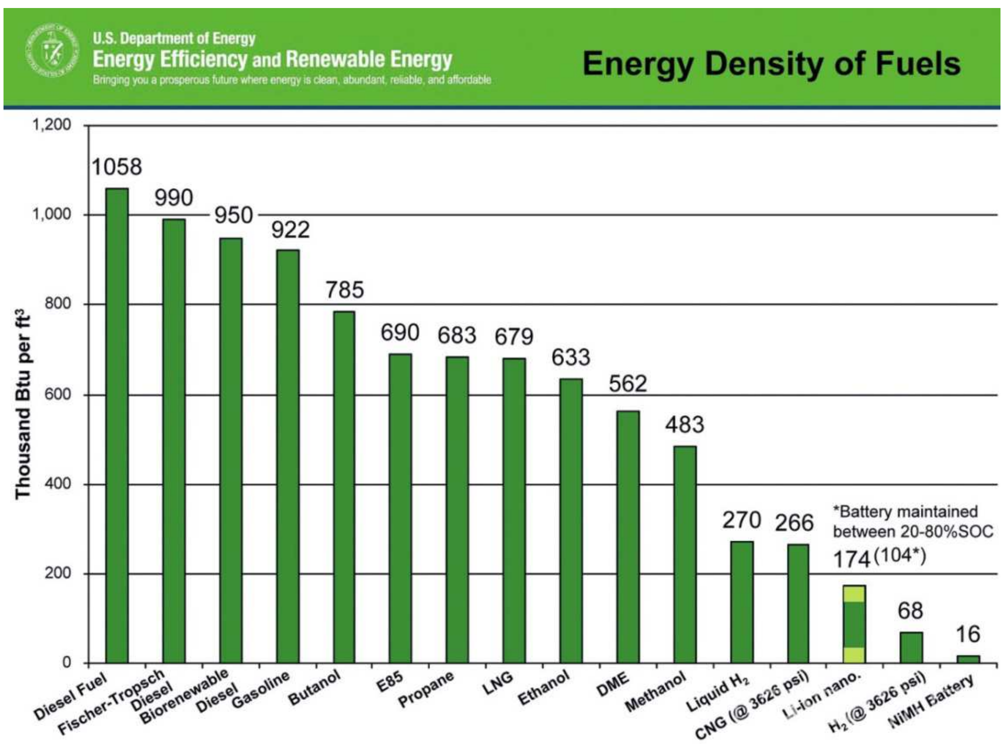


Figure 17: Energy density of various transportation fuels (US DoE)

JB Hunt Transportation owns over 12,000 tractors and produced a white paper outlining their experiences with natural gas vehicles. [50] They describe the incremental cost to purchase a tractor powered with a 12L natural gas engine as being between $50,000 USD and $90,000 USD where $22,000 to $61,000 of these increases are principally related to the fuel tanks. This incremental capital acquisition cost and the unknown residual value of the vehicles makes the return on investment (ROI) difficult to reconcile if natural gas prices rise, relative to the diesel prices that were used for the original ROI calculations/estimates. Additionally, there is an inherent fuel consumption increase of between 15% to 20% [50] with natural gas engines compared to SCR equipped diesel engines, of the same displacement, since natural gas engines are spark ignited, which are inherently less efficient. Higher in cylinder temperatures allow SCR equipped vehicles to typically burn as much as 5% [17] [18] less fuel than similarly sized EGR equipped vehicle. The use of SCR fluid (DEF) does mandate higher ongoing consumable costs compared to EGR equipped vehicles so the ROI comparisons are sensitive to not only fuel costs but to DEF costs as well. Therefore the increase in fuel costs between natural gas engines and clean diesel engines can vary depending on the type of emissions reduction equipment on board, making the ROI calculation even that much more difficult to accurately determine.

Reliable price information for DME tanks was not obtained but given their size and construction it is clear that they will be significantly less expensive than the tanks required for any natural gas powered vehicle and likely similar to the price of LPG tanks but more than diesel tanks.

4.1.1 **Compressed Natural Gas**

Compressed Natural Gas (CNG) is the variation of natural gas that is stored at pressures as high as ~3,600 psi (~3,000 psi in Europe) and has a DGE of approximately 3.98. As an example, 58 litres of CNG would be required to provide the same energy as 15 litres of diesel fuel.

The fuel is considered a pipeline fuel as it cannot be trucked due to its extremely high pressure. This means that operators who wish to fuel their vehicles with CNG must build a high pressure pumping station fed by a natural gas pipeline. CNG must be stored in special tanks on the vehicle that are constructed to withstand very high pressures and harshness of driving over rough roads in inclement weather. These tanks are extremely strong and much heavier and more expensive than other fuel tanks. The details and examples of CNG tanks and comparisons to DME tanks can be found in Section 6.7.1. CNG is gaining popularity with operators as prices decrease and infrastructure increases. [28] The specifics of how CNG is used as a heavy duty vehicle fuel have been presented in Section 7.1.

In 2004 the US National Renewable Energy Labs (NREL) conducted emissions tests [51] on twelve different transit buses. Some of the buses were powered by lean burn natural gas engines and oxidation catalysts whereas the diesel buses were powered by ULSD fuel and contained catalyzed particulate filters and some had EGR as well. The results of the study showed that emissions of NO_x and PM were significantly reduced when compared to diesel (49% and 84% respectively for one set of buses). The emissions of CO and HC were also found to be lower for CNG when compared to diesel. NMOG emissions were also found to be very low for CNG.

According to 2013 statistics, when pump diesel cost $1.05 per litre in the USA, the equivalent cost for CNG was 61.9 cents per litre (DGE). The US Department of Energy publishes a quarterly report called ‘Clean Cities Alternative Fuel Price Report’. [52] The fall 2014 issue of the report highlights many regional and national fuel trends (all listed in DGE) and clearly shows that the price of CNG has remained extremely stable, between $2.00 and $2.45 per gallon, over the past five and a half years (currently $2.45 per US gallon) compared to all other listed fuels. Similar trends can be seen in the ngvamerica.org graph (Figure 18) showing the 15 year trend of fuel prices, however, note that this figure should be used for trends only as the actual numerical values are listed in gasoline gallon equivalent (GGE) which are not consistent with the DGEs listed elsewhere in this document. Figure 18 shows how the price for CNG has not changed significantly over the past five years while diesel and gasoline prices were highly inflationary and also somewhat erratic. The price of CNG has more than doubled in the last 15 years in the US though.

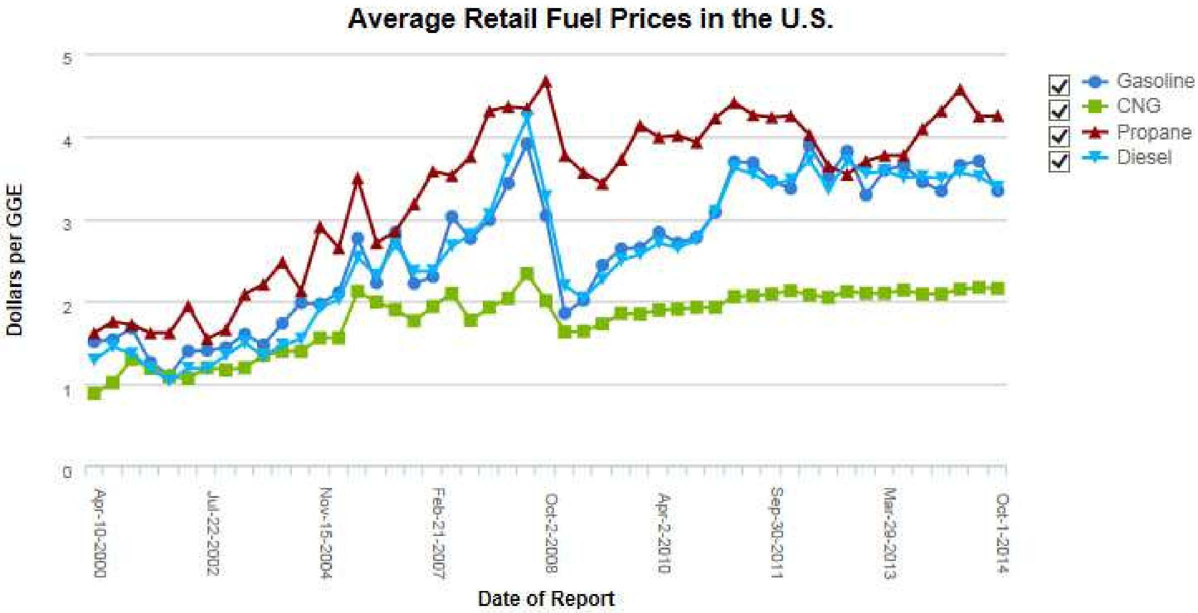


Figure 18: 15 year US price trend of various fuels (ngvamerica.org)

4.1.2 **Liquefied Natural Gas**

Liquefied Natural Gas (LNG) is the variation of natural gas that is stored at cryogenic temperatures as low as -160 °C (-260 °F) and has a DGE of approximately 1.56 and is pumped at pressures between 30 psi to 120 psi. As an example, 26 litres of LNG would be required to provide the same energy as 15 litres of diesel. Unlike CNG, LNG can be trucked from site to site in its cryogenic state and then dispensed into tanks at a station for delivery onto the vehicle. However, the tanker trucks and trailers that are used to transport LNG are typically significantly more expensive than conventional tankers that haul, say, gasoline and diesel fuel.

LNG is generally about 95% methane, with ethane, propane, butane and nitrogen forming the remaining 5%. [53] LNG is a self-refrigerated product in the sense that it will boil off to maintain pressure, which in turn maintains the temperature. Despite the insulation layer in the tanks, however, once LNG is stored on board a vehicle it must be used within five to seven days or else it will simply vent off trying to maintain its cryogenic state. LNG can be used for extended periods of time on large ocean-going vessels because there is adequate space and weight carrying capability to store large coolers that are used to maintain the fuel's low temperatures. The details and examples of vehicle mounted LNG tanks can be found in Section 6.7.1 and the specifics of how LNG is distributed as a heavy duty fuel are presented in Section 7.2.

According to 2013 statistics, when pump diesel cost $1.05 per litre in the USA, the equivalent cost for LNG was 64.8 cents per litre (DGE), which is approximately 3 cents per litre higher than CNG. The increase in cost for LNG over CNG is typically related to the conversion to the liquid phase and the insulation needed to maintain cryogenic properties.

Some maintenance facts are shown in this section but are also true for CNG. An article in Wheeltime magazine [54] featuring maintenance managers for some major US fleets describes some of the maintenance issues that can be experienced with natural gas engines. According to fleet managers at Ryder Truck, Penske and Fedex, it can cost approximately 1.5 cents more per mile (0.94 cents per km) to maintain (maintenance but not operations) a natural gas vehicle than a comparable diesel vehicle. JB Hunt Transportation [50] lists these costs as between 2 and 4 cents per mile. As with DME, the lubricity of natural gas is significantly less than that of diesel fuel. This means that special engine oils are required to keep engine seals in good working order and engine oil change intervals must be reduced. Not only does this increase labour costs, but the oils used in a natural gas engine are 20% more expensive than those in conventional diesel engine (which themselves are 20% more expensive than oils used for gasoline engines). Additionally, the spark plugs required for use in an LNG engine are very expensive and must be handled with extreme care to avoid damage and should be replaced every 100,000 km. In essence, these fleet managers treat LNG engines more like gasoline engines than a diesel engine, whereas a DME engine should be maintained more like a diesel engine.

LNG is pumped into a vehicle as a super cooled, liquefied gas therefore personnel who are refueling vehicles must wear protective equipment such as face shields and gloves.

4.2 Liquefied Petroleum Gas

Liquefied Petroleum Gas, or LPG, is propane (C_3H_8) or butane (C_4H_{10}) and has been used for years as a heating or cooking fuel but can also be used to power vehicles. Unlike CNG, LPG and DME have similar working pressures and can use the same pressure vessels or can be combined in the same vessel and can use the same pumping infrastructure. [55] [56]

LPG has a lower volumetric energy density (1.55 DGE) than diesel or gasoline (see Table 9) but a higher energy density than DME and CNG therefore it can compensate for the low energy density of DME when LPG is blended with DME and the fuel consumption rate can be improved by LPG blending [19].

Like natural gas, LPG is a fossil fuel and is thus considered to be non-renewable. Under normal atmospheric conditions, LPG vapour is 1.5 heavier than air and therefore vehicles fueled by LPG are generally not allowed to park in underground garages due to the risk of fuel leaks that could cause LPG to pool or settle at floor level. LPG is also an oxygen displacer and can suffocate persons who are trapped inside a building where LPG has leaked. Above 97 °C the fuel cannot be stored as a liquid at any pressure. When LPG changes from a liquid to a vapour its volume increases by a factor of 270. LPG has no odour but an odourant is added to alert persons to a possible leak. Ignition temperature of LPG is between 450 to 510 deg C, which is nearly twice as high as gasoline but slightly lower than LNG.

Like, natural gas, LPG vehicles use a sealed fuel pressurized system therefore there are no evaporative losses such as in a gasoline powered vehicle where vapours must be trapped in a charcoal canister.

Tests conducted by Saraf et al [57] demonstrated that CO, NOx, HC and CO_2 emissions decreased but other tests by Park and Lee [19] revealed that levels of CO and HC were higher due to incomplete combustion of a DME-LPG blended fueled engine. Since many LPG engines are in fact conversion kits from gasoline powered engines they may not always be tuned to run optimally on LPG, thus producing higher levels of CO and HC. Nonetheless, LPG does consistently produce very low levels of PM.

According to 2013 statistics, when pump diesel cost $1.05 per litre in the USA, the equivalent cost for LPG was $1.11 per litre (DGE). Although not nearly as prevalent as gasoline or diesel, propane dispensing sites began appearing in Canada in the early 1980s and is considered a more mature infrastructure than CNG or LNG. [55]

5 ORGANIZATIONS INVOLVED IN DME DEVELOPMENT

There are many types of organizations involved with DME both past and present. Most of the important academic DME related research has already been mentioned and referenced in this document. Vehicle manufacturers who will ultimately build, sell and maintain DME powered vehicles are also involved in research and development of DME and will be discussed in Sections 5 and beyond.

For the most part, DME vehicles have been limited to those produced specifically for research studies, and most of these have taken place in Asia although some work has been done in Europe and North America. As previously discussed, Volvo and Mack trucks have each identified DME as a promising alternative fuel, however, neither manufacturer has committed to a firm date to begin production for North America. Further field testing (and presumably infrastructure development) are required in order for the OEMs to be confident that DME fueled vehicles can be successfully marketed and fielded in a market dominated by diesel powered vehicles. A list of some of the major vehicle and product development projects includes:

- The Penn State/VolvoOak Ridge 2014 *Emissions and Performance Benchmarking of a Prototype Dimethyl Ether-Fueled Heavy-Duty Truck* mentioned already [22];
- In Europe, several countries, such as Sweden, Netherland, and Austria, have headed the development of DME-fueled vehicles including trucks, buses, and passenger cars [19];
- In South Korea, trucks, buses, and passenger cars using DME fuel have been developed by research institutes and universities [19];
- Pyo et al. developed a DME fuel supply system and a modified heavy-duty DME-fueled bus using an in-line pump [19];
- In addition, C.S. Lee of Hanyang University developed a DME passenger car, and KATECH developed a medium-sized vehicle using DME fuel;
- The Volvo/Chemrec black liquor DME project mentioned various times in this report [1];
- Recently, the International Energy Agency conducted a project for DME fuel titled 'Fuel and Technology Alternatives for Bus' (Annex 37, IEA Implementing Agreements on Advanced Motor Fuels). In addition, the International DME Association (IDA) was established in 2001, and many research institutes, universities and companies researching DME fuel participate in the IDA. [19]
- AVL (Austria) has promoted research and development of DME-fueled engines since 1995; [19]
- Development of a DME-fueled city bus [12] with an oxidation catalytic converter in 2000, based on a VOLVO DH10A engine [19]
- In the USA, a DME-fueled shuttle bus demonstration project was carried out from 1999 to 2002 by a group including members of Pennsylvania State University, Air Product and Chemicals, DOE (Department of Energy), Navistar, and Caterpillar. The project team focused on the conversion of the shuttle bus to a DME-fueled vehicle, and they used DME-diesel blended fuel to compensate for the weak lubricity and viscosity of DME fuel [19] [30];
- In 1996, the JFE manufactured a DME-fueled truck as a part of a NEDO (New Energy and Industrial Technology Development Organization) project [19];

- From 1998 to 2001, a heavy duty DME-fueled truck was manufactured by the cooperation of the Nissan Diesel Company and NTSEL (National Traffic Safety and Environment Laboratory [19] ;
- Kinoshita et al. [133] reported on the development of a retrofitted DME-diesel engine operating with a rotary distributor fuel injection pump [19];
- The DME Vehicle Promotion Committee (DMEVPC) was established in Japan in March, 2006, organized by private companies from various sectors of industry in order to develop and research DME vehicle operation [19];
- Delphi (UK): Development of a DME fuel injection system together with Volvo. [1] [8];
- Energy Technology Centre in Pitea°, ETC (Sweden): Laboratory support to plant operation and DME delivery [1];

Some of the more interesting DME related projects have also been listed in Table 10.

Table 10 – Some major DME vehicle development projects [19]

Year	Authors	Manufacturer (Nation)	Type/engine displacement	Technology/specification	Ref.
1998	–	JFE Holdings (Japan)	NKK Cargo truck 4636cc	In-line pump	[h]
1998	–	Isuzu Advanced Engineering Center Ministry of Land, Infrastructure and Transport (Japan)	Medium-sized bus 8226cc	Common-rail 48 passengers	[h]
2000	Hansen et al.	Danish Technological Institute Haldor Topsoe A/S Statoil A/S Volvo Truck & Bus Group (Sweden)	City bus 9600cc	Common-rail type DH10A engine In-line 6 cylinder Turbocharged	[12]
2001	–	Mitsubishi, JOGMEC[a] Iwatani Int' Corp (Japan)	Cargo truck 4214cc	Distribution pump	[h]
2002	–	Isuzu (Japan)	Medium-sized truck 7166cc	In-line pump	[h]
2002	Eirich et al. Chapman et al.	The Penn. State University Air Products and Chemicals (USA)	Shuttle bus 7300cc	HEUI[b] Navistar T444E engine (V-type 8 cylinder) Turbo diesel engine	[131,132]
2003	–	Hino Motors NEDO[c] (Japan)	Hybrid bus 7961cc	Common-rail 77 passengers	[h]
2004	–	Isuzu (Japan)	Cargo truck with crane 4777cc	Common-rail	[h]
2004	–	Nissan diesel NTSEL[d] (Japan)	Large-sized cargo truck 6925cc	In-line pump w/$DeNO_x$ cat.	[h]
2005	Huang et al.	Shanghai Jiaotong Univ., Shanghai Automobile, Shanghai Diesel (China)	Shanghai city bus 8300cc	In-line pump Turbocharger Inter-cooler	[139]
2005	Goto et al.	AIST[e], JOGMEC (Japan)	Medium duty truck 7166cc	In-line pump In-line 6 cylinder Natural aspiration	[134]
2006	Pyo et al.	KIER[f] (Korea)	Truck 3ton	In-line pump	[135]
2006	Tsuchiya et al.	Nissan Diesel Motor, NTSEL (Japan)	Heavy-duty truck 6925cc	Jerk pump type FE6T engine (Nissan) In-line 6 cylinder Turbocharger	[16]
2008	Pyo et al.	KIER (Korea)	Bus 8,071cc	In-line pump 6 cylinder	[136]
2009	Lee et al.	Hanyang University (Korea)	Passenger car 1582cc	Common-rail In-line 4 cylinder	[137]
2009	Kang et al.	KATECH[g] (Korea)	SUV 1991cc	Common-rail EGR, VGT	[138]

[a] JOGMEC: Japan Oil, Gas and Metals National Corporation.
[b] HEUI: Hydraulically actuated electronically controlled unit injectors.
[c] NEDO: New Energy and Industrial Technology Development Organization.
[d] NTSEL: National Traffic Safety and Environment Laboratory.
[e] AIST: National Institute of Advanced Industrial Science and Technology.
[f] KIER: Korea Institute of Energy Research.
[g] KATECH: Korea Automotive Technology Institute.
[h] http://www.dme-vehicle.org/eng/index_eng.html.

6 OPERATIONAL CONSIDERATIONS OF DME USE

6.1 Required Vehicle Modifications

The physical and chemical properties of DME as they relate to the product itself were discussed in Section 3. However, in order for the fuel to work correctly in a vehicle, consideration must be given to how a DME powered vehicle would need to be modified, or in the case of a new vehicle, constructed. This section will outline the specific DME fuel components as well as any ancillary vehicle equipment that must be altered, added or removed in order to provide a vehicle operator with at least the same level of vehicle performance as they currently have with diesel fuel.

6.2 DME Specific Equipment

This section will outline the equipment that must be added, modified or removed as a direct result of using DME as a fuel for heavy haul transport. Issues relating specifically to the weight of the tank have been covered in Section 6.7.1.

6.2.1 Fuel Tank

The most obvious and visible alteration to any DME powered vehicle is the removal of the diesel fuel tank and the addition of the DME fuel tank. The tank must be a pressure vessel and should be corrosion (salt/oxidation) resistant and positioned such that the exposure to road salt is minimized. [37]

As discussed in Section 3, in order for DME to function correctly and to provide the necessary vehicle range, the product must be compressed and stored as a liquid. Because DME fuel exists as a gas phase under atmospheric conditions, this necessitates the addition of at least one pressure vessel that can withstand pressures on the order of 5 bar (~75 psi). Although this is still a pressure vessel it is considered to be in the same pressure range as, say, a home barbeque propane tank. Compressed natural gas (CNG) engines require pressure vessels that can withstand pressures of 3,600 psi which is a different class of pressure vessels altogether that require significantly more engineering and handling expertise than a DME tank. An example, taken from the Volvo Group, is shown in Figure 19 and illustrates that the DME tank is visually somewhat similar to the diesel tank it replaces with notable differences being the lack of filler cap, the addition of a sight glass and the hemispherical end caps. The weight and dimensions of DME and conventional diesel tanks are discussed in Section 6.7.1.

Another feature of the DME tank is a blowdown valve to vent the DME in the event of a fire thereby preventing an explosion of the fuel tank from over-pressurization caused by excessive temperatures. [37] Frangible disks are also likely to be used, as seen on the ends of the tank in Figure 19. These disks act as pressure relief valves and blow off in the event of a significant over pressure situation and exhaust the product safely.

As demonstrated in previous sections, DME has roughly 66% of the heating energy of diesel by mass and only about 53% by volume, meaning that DME tanks must be larger than diesel tanks in order to maintain vehicle range. Conversely, if the size of the tank(s) is matched to those of diesel, the range will be reduced accordingly.

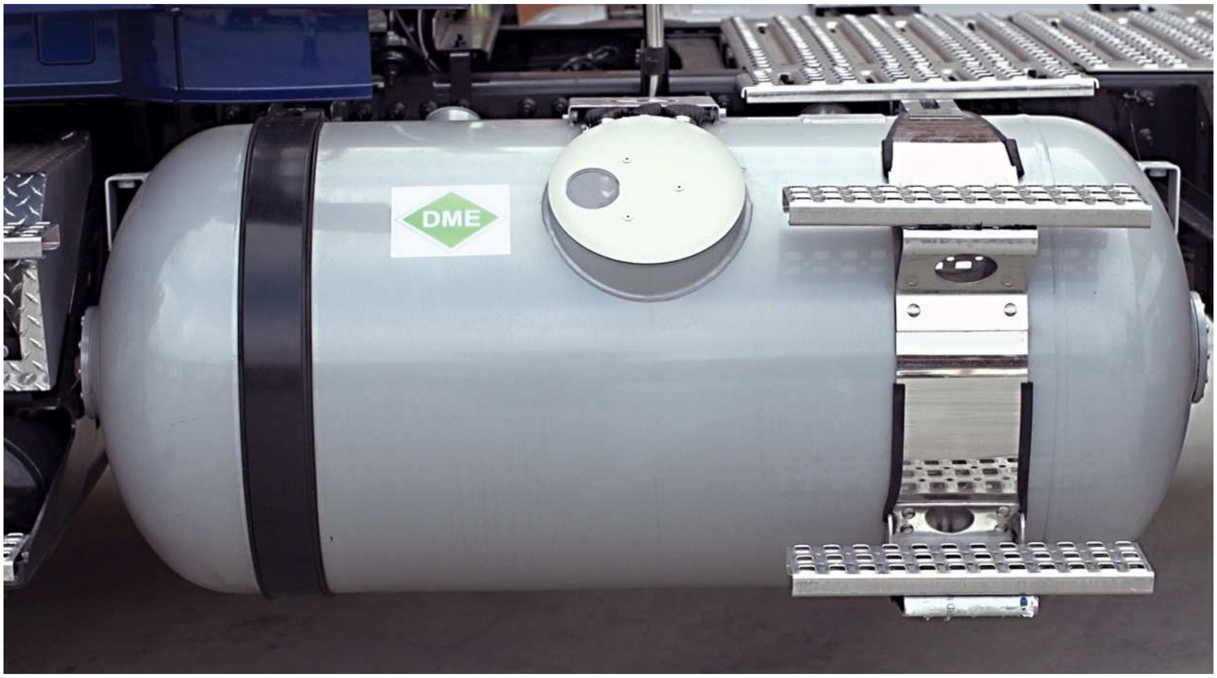


Figure 19: Example of DME fuel tank (courtesy Volvo Group)

In 2001, McCandless et al [58] developed a novel DME fuel tank called a ‘two fluid thermodynamic pump’ which greatly simplified the method by which DME was pumped into the fuel injection system. Similar to a cottage/rural style plumbing water tank that uses a bladder as a means to provide a constant pressure inside the tank, their system included a 40 litre (water volume) aluminum tank with a diaphragm separating the DME working side of the tank from the pressure side of the tank which contained a vapour-liquid mixture of propane. The propane served to keep DME in a subcooled liquid state because the vapour pressure of propane is higher than that of DME at all temperatures. The propane also acted as the pump to thermodynamically pump the DME from the tank to the high pressure injector pump. The use of this type of tank reduces the number of moving parts and also reduces the number of parts that could be damaged by the lack of lubricity in the DME.

6.2.2 **Fuel Additives**

As discussed in Section 3.2.3. in order to use DME fuel in a diesel engine system, the fuel injection system needs to be modified and the DME fuel viscosity and lubricity increased [19] via additives that change the chemical composition of DME. Unlike diesel exhaust fluid (DEF) used in SCR systems, it will be the responsibility of the fuel supplier, rather than the operator, to ensure proper lubricity of the fuel since it is injected with the fuel, rather than in the exhaust downstream of the engine. The use of fuel additives will not alter the weight or dimensions of a heavy vehicle.

6.2.3 **Fuel Injection and Fuel Pump**

The physical and chemical properties of DME are such that it cannot be used in a conventional diesel engine without significant modifications to the engine and the vehicle's fuel delivery system. Although most manufacturers claim this is a relatively straight forward process, there are still many steps that must be taken to ensure proper combustion of DME. Most notably, a DME engine requires a modified fuel delivery and injection pump/timing system [19] in order to function correctly. Some of these modifications on a Volvo engine [59] are shown in Figure 20.

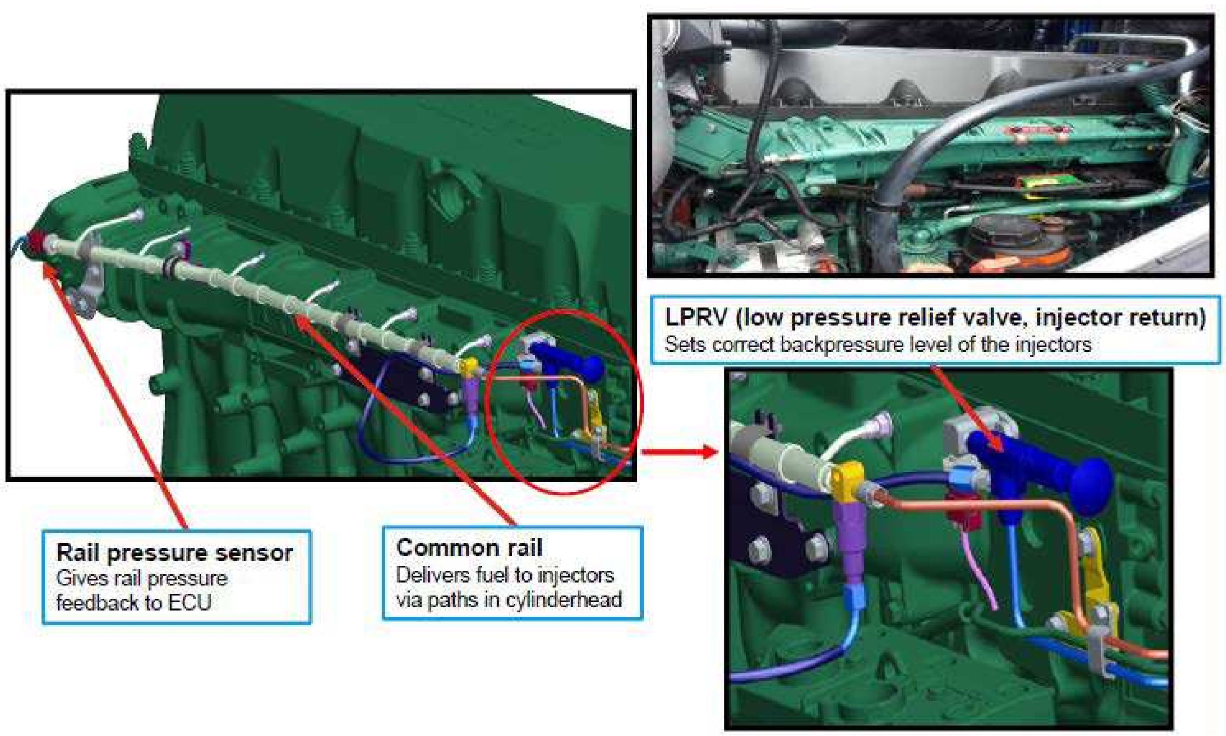


Figure 20: Example of DME fuel injection modifications (courtesy Volvo Group)

Many sources were reviewed [21] [23] [34] [35] [36] [60] outlining the steps necessary to adapt the fuel injection pump and injectors for use with DME. Many other sources were overly academic for this report and very specific to certain test cases. As discussed in Section 3.2.6.2, Tsuchiya and Sato [45] integrated a DME powered engine into a 20 ton freight truck. Their design included a jerk style inline injector pump [45], [61] integrated with spring loaded needle. The amount of fuel supplied for each power stroke was about twice the normal amount and was primarily achieved by increasing the size of the injector nozzle from 0.28 mm to 0.37 mm which doubled the opening area. The plunger of the pump was treated with a sulfur compound to compensate for the low lubricity of DME and the pump itself had a dedicated oil sump to reduce friction.

Studies performed by Park and Lee noted that the DME injection duration is longer than that of diesel because of the pressure drop of DME [19] and the peak injection rates of both fuels increase at higher injection pressure and is reached earlier at low injection pressures [19]. To compensate, the energizing duration of the injector must increase by approximately 37% compared to that of the diesel fuel, and the injection mass of the fuel is also different [19]. As a result of these factors, the injection duration of DME is longer and the peak injection rate of DME can be reduced since DME has lower fuel density than diesel fuel [19]. This means that the existing fuel injection mapping, duration and injection timing must all be altered before DME can be used in a diesel engine. The results of these tests are shown at Figure 21 and illustrate how fuel injection mapping must be altered when DME is used in place of diesel. The three charts represent the following, from top to bottom: profiles of injection rate, effective injection velocity, and energy supply rate for DME and diesel fuels with a constant energy input (mDME ¼ 11.9 mg/cycle, mDiesel ¼ 8 mg/cycle).

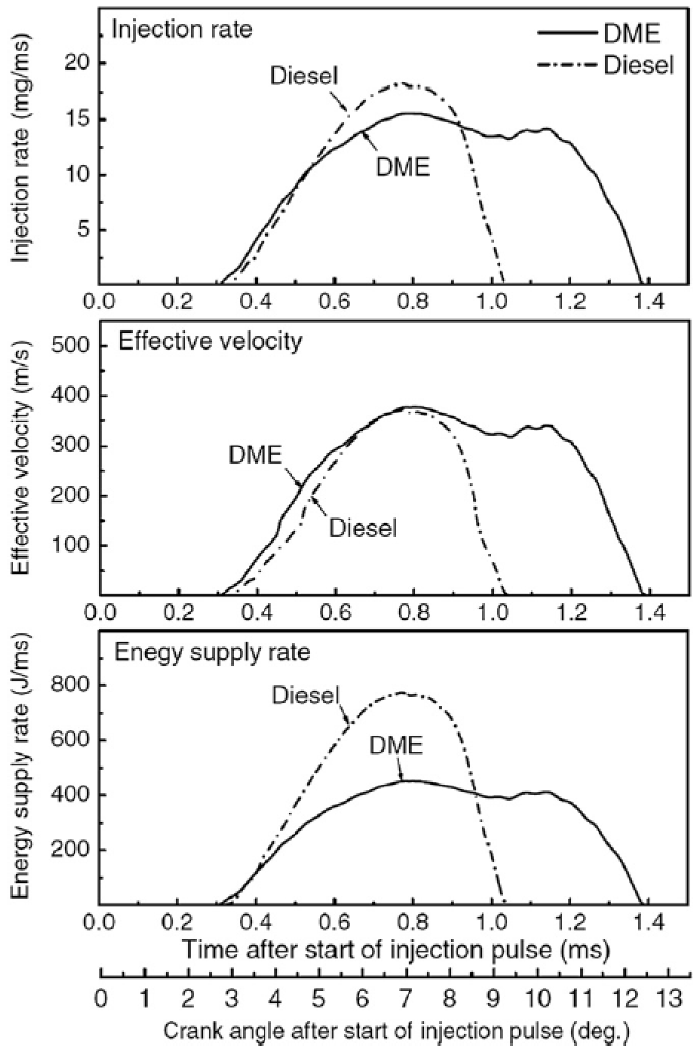


Figure 21: Fuel injection characteristics, diesel vs. DME

They concluded that a common-rail type high pressure fuel injection system with electronic control is the best option for a system for use in a DME engine because it will be easier to optimize the injection timing of the fuel and the energizing duration of the injector, which are related to the mass of the injected fuel and rate of injection [19]. The components of a high pressure fuel injection system consist of a high pressure injection pump (pressurized fuel is sent to the common-rail), the common-rail control valve, high pressure fuel lines and injectors, the fuel cooling system, the purge system including purge line and tank, and the injection controller, which uses an electronic signal. [19] It is likely that all of these components would need to be replaced or modified on a conventional diesel engine if DME was chosen as the fuel.

One important factor to note is that all of these fuel system modifications make it difficult, if not impossible, for OEMs to offer a multi fuel platform (such as GM's "Flexfuel" concept) that includes DME as one of the flexible fuels. In other words, once a vehicle has been converted to operate optimally on DME alone, it can only operate on DME unless those modifications are reversed and the original equipment added back on. This will be a critical point to consider until such time as DME is widely available along long haul trucking networks.

6.3 Other Equipment

This section will outline any ancillary equipment that must be added, modified or removed as a direct result of the DME itself. Aside from the fuel tank and injector equipment, many other devices must be considered for a successful transition to DME. The following is a list of items that will likely need to be considered on a DME powered vehicle:

- Protective metal coverings should be placed along the DME fuel line from the fuel storage reservoir and the high pressure injection pump to prevent possible puncture of the line and the potential for a fire; [37]
- Fuel lines should be modified in order to prevent the leakage of fuel and the wear of mechanical component as a result of the low viscosity and lubrication of DME [19];
- Since DME can dissolve many products, rubber and elastomer seals must be replaced throughout the vehicle on all 'fuel-wetted' components in order to reduce the risk of material decay due to the non-compatibility with DME. In some cases this will require the use of metal to metal valve seating rather than seats manufactured from elastomers. The use of common sealing material applied in conventional diesel injection system cannot prevent the leakage of DME, and the selection of improper sealing material for DME can cause the wear of moving part in the fuel injection and supply system; [19] [37]
- In order to reduce the risks described in the previous bullet point, the use of Teflon and PTFE (poly-tetrafluoroethylene) compounds for sealing material in the DME injection and supply system is essential as they are inert to DME [19] and will prevent leaks and premature wear;
- Substantial over-pressure capability should be designed into all DME fuel system components to allow for pressure increases generated by temperature fluctuations in the fuel system and the high expansion rates of DME; [37]
- DME exiting the fuel injection nozzle return line must be vented to atmosphere well away from the high temperature engine components and other sources of ignition; [37]
- All fittings should be butt-welded ANSI flanges; [37]
- Non-sparking metals (stainless or brass) should be used for the DME fuel tank, fuel line fittings and valves to eliminate spark generation from wrenches which might lead to a fire situation; [37]
- All wrenches used for assembling/disassembling the DME fuel system should be non-sparking; [37]

- The vehicle refuelling system should have a provision for grounding to the vehicle DME fuel system such that there can be no electrostatic charge potential between the vehicle and the vehicle refueling system. Electrostatic charge buildup can lead to an electrical discharge in the form of a spark which might lead to a fire situation; [37]

- All DME fuel system components, including the DME fuel reservoir, fuel line fittings/valves and fuel filler line should be electrically continuous and grounded to prevent electrostatic charge buildup. Due to the poor electrical conductivity of DME, DME fuel system components are susceptible to electrostatic charge build. Electrostatic charge buildup on fuel system components can lead to an electrical discharge in the form of a spark which might lead to a fire situation; [37]

- A fuel storage level fill shutoff system should be employed to ensure that the reservoir is not filled above the 80% full level thereby allowing room for expansion of the DME during varying ambient temperature conditions. As with LPG, DME has a high thermal expansion rate and as such it is necessary to leave 20% additional reservoir volume to allow for DME expansion during temperature fluctuations; [37]

- A pressure relief valve should be installed in all locations where the DME fuel is contained including the fuel reservoir and the fuel lines between shutoff valves. The pressure of DME in a confined space varies substantially with temperature. High temperatures including fire situations may result in excessive DME pressures and fuel system ruptures unless a pressure relief valve is installed; [37]

- Remotely operated emergency shutoff (fire-safe) valves, constructed from DME compatible materials, should be used to allow the operator to shut off the DME supply in the event of a fuel line rupture and/or fire; [37]

- The DME purge tank should be located such that its vent is outside the vehicle so that DME is not vented in the area of high under hood temperatures, exhaust system components and electrical system components. During engine operation the DME in the purge tank would be combusted in the engine at a controlled rate; [37]

- Threaded fasteners and bracketry used to attach DME fuel system components should be corrosion (salt/oxidation) resistant; [37]

- Although the fuel that returns into a conventional diesel fuel tank from the engine is heated, diesel fuel is typically contained within the entire fuel system at temperatures that are relatively close the ambient conditions. However, DME's properties can change from liquid to vapour and back again at various locations in the fuel supply system meaning that thermal cycling is much more common than in diesel systems. This can cause fatigue cracking in certain components such as valves; [37]

- In some cases it may be necessary to add fuel coolers or temperature control units to manage these thermal stresses [19].

6.4 Equipment Removal

Because of its implication with heavy vehicle weights and dimensions, all aspects relating to the possible removal of EGR, SCR and DPF/traps may be found in Section 6.7.2.

6.5 Engine Equivalent Fuel Consumption and Range for DME

The concept of a diesel equivalent gallon (DGE) must be considered when fuel consumption data are reviewed. Because DME has approximately 53% of the energy content of diesel by volume, the fuel consumption calculated data are also approximately 53% that of diesel. For example, the data from the joint Penn State/Volvo/Oak Ridge testing revealed fuel consumption test results of 2.66 mpg and 2.98 mpg for the 60 mph and HHDDT test cycles, respectively. [59] At first glance these values seem unacceptably low by current highway heavy duty standards. However, when the DME's DGE value of 1.88 (Table 9) is applied, these values correspond to fuel consumption rates of 5.00 mpg and 5.60 mpg respectively, which are consistent with current heavy duty tractor fuel consumption values.

The two year Volvo/Chemrec study results noted that fuel consumption was equal to that of heavy haul diesel, once the conversion rate had been applied. [42] The authors claimed a useful range of approximately 800 km using twin 465 litre tanks. Assuming a DGE of 1.88 this means the vehicles travelled, on average, 800 km using 494 equivalent litres of fuel, or a fuel consumption of 61.83 l/100 km. These values are higher than the average for such vehicles in Canada [62] but not unreasonable given that terrain, speed and temperature data are not presented for this Swedish study.

Tsuchiya and Sato recorded an average of 54.54 l/100 km for their testing of a 20 ton truck powered by DME. [45]

The president of one of the United States' largest producers of DME, Oberon (Section 7.3.5), concedes that their DME production is intended for fleets whose vehicles return home every night. [63] She goes on to say that, due to the lower energy density of DME, a practical maximum range for a DME vehicle is approximately 1,000 km which is significantly less than most highway long haul tractors using similarly sized tanks.

6.6 Changes in Maintenance Requirements

Operators will need to know how DME affects the maintainability and reliability of their fleet of vehicles in the following manner:

- Will certain parts require replacement or rebuilding more often;
- Will fuel system inspections and adjustments need to be performed more often;
- Will spare parts be more expensive;
- Will special mechanic training be required to handle DME;
- Will DME affect the longevity and quality of the engine oil, thus affecting the overall health of the engine;
- Will special maintenance bays be required when working on DME vehicles; and

- How will overall maintenance costs compare to those of diesel, LNG. CNG and LPG fueled vehicles.

The bullet points listed above have been left as questions for now because insufficient data could be found to make an accurate and quantitative assessment of these factors and how they will affect fleet owners and maintainers. The authors of the joint Volvo/Chemrec [1] two year DME study and field tests concluded that the lack of DME lubricity required maintenance intervals to be shortened in order to inspect and repair fuel pump equipment and to ensure the fleet continued to operate optimally. However, the authors noted that the performance of the fuel injection system far exceeded their expectations. Nonetheless, the research team are currently searching for methods to improve lubricity such that maintenance intervals can be lengthened to those currently used by diesel powered vehicles. No other DME specific maintenance issues were reported by the authors.

Some of the specific maintenance topics have been presented below.

6.6.1 Engine Oil

One of the principal advantages of using DME is the reduction in soot, or PM. In a conventional diesel engine, the formation of in-cylinder PM causes wear on the engine as carbon particles scrape against the moving parts inside the engine. Many of the particles are trapped in the engine oil filter, however, particles less than about 25 microns will pass through the filter and possibly damage engine components as a result of blow-by that makes its way back into the crankcase. For this reason, engine oil designed for diesel engines is significantly different than that for gasoline engines. Diesel engine oil must clean the engine by trapping these excess PM blow-by particles in suspension before they can damage the engine. However, if diesel engine oil is used in a gasoline engine, the extra additives will try to ‘clean’ an already clean engine and this may affect the seal between the piston rings and the cylinder liner which can reduce engine compression and affect engine performance. Similarly, if a gasoline engine oil is used in a diesel engine it will not adequately clean the excess PM particles and engine wear will result. To distinguish between the two forms of oil, and reduce the risk of using an incorrect product, oils are classified by the American Petroleum Institute (API) and are identified as compression ignition, with the letter ‘C’ shown in the upper half of the label of Figure 22 to the right, and ‘S’ for spark ignition engines, shown in the left label of Figure 22.

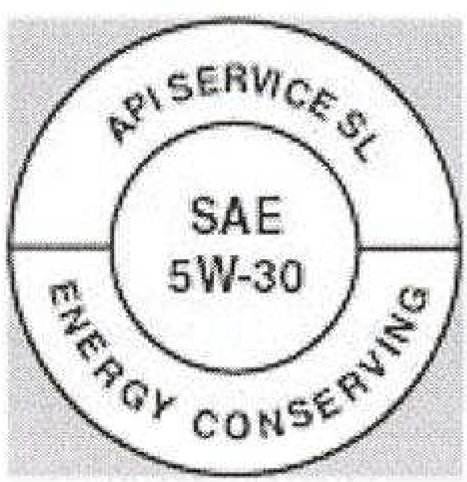


Figure 22: American Petroleum Institute oil designations

Some research [24] has shown that although there is almost no soot formation with DME, the soot that is formed tends to be in the nano range which is extremely small in diameter and can easily flow through engine oil filters. No research could be found documenting the way in which nano soot particles from DME fuel could possibly cause engine wear over the long term and no research could be found comparing these effects to the effects of burning conventional diesel in an engine for long periods of time.

The results of such a study could provide evidence to suggest that the oil change intervals could be changed when soot-free DME is used rather than conventional diesel. This could be a shortening of the interval if it is found that more nano-particles are created by DME or it could be a lengthening of the interval if it is found that burning DME creates insufficient absolute levels of soot to cause engine wear, despite the fact that greater than 90% of the soot in DME combustion is in the nano regime. [24]

It will also be of interest to determine if conventional oils used for gasoline engines could, or should, be used in a DME powered engine in place of traditional diesel oils owing to the reduction in PM. The use of oils that clean PM particles may not be necessary and could in fact reduce engine performance, as explained above. These topics have been suggested for further study since NRC-AST could not locate any research studies that quantified these effects.

6.6.2 **Air Filters**

Based on the information presented in Section 3.2.1, approximately 94% of the volume of air that is ingested into a diesel engine will be required for the same engine, producing the same power but burning DME. Given the relatively similar air volume, it is not likely that service intervals for air filters/cleaners will need to be adjusted for DME compared to diesel fueled engines but nonetheless it does mean that approximately 7% less air, and presumably 7% less dirt and contaminants, will be ingested into a DME engine compared to diesel, if all other factors remain the same.

6.6.3 **Changes in Mean Time to Failure**

Vehicle designers, operators, maintainers and parts suppliers will be need to fully understand how DME fueled vehicles will differ from diesel vehicles in terms of the replacement schedule of parts and parts availability, for both corrective and preventive measures. Diesel engines are sufficiently mature that the mean time between failure (MTBF) of all parts is well understood and parts inventories are maintained to specific levels to match the demand. The need to monitor part failures will include short term performance such as pumps and injectors as well as the long term health of the DME pressure tank that may, or may not, be exposed to road sand and salt.

One of the biggest challenges to maintaining current levels of vehicle reliability will be the lubrication of the fuel. Insufficient lubricity of DME fuel can cause significant wear on the rotating parts of the fuel injection pump and feed pump system in the engine [19] causing premature failure of many parts in the fuel system. This could lead to an increase in costs and an increase in vehicle breakdowns on the highway if the lubricity issues are not solved. Kato et al studied fuel flow through the injector nozzles and concluded that cavitation in the injection nozzle is more frequent with DME than with diesel fuel which necessitates the use of DME specific nozzles. [60] In its simplest form, cavitation can cause paint to flake away on components such as propellers, however, left unchecked, cavitation can eat away at metal surfaces (Figure 23) until parts are no longer able to function correctly. In the case of fuel injection components, this can cause improper clearances and can lead to poor spray fuel penetration characteristics with DME at high engine speed and load [19]. In its worst form, DME induced cavitation could also lead to complete perforation of fuel components which would lead to fuel leaks (either internal or external). Designing a DME system that is considered reliable and maintainable will also rely heavily on a complete understanding of the sealing and gasket materials used on the engine's fuel delivery system. Many studies [36] [61] [64], have demonstrated the complete incompatibility of conventional sealing material with DME which, if left unchecked, would undoubtedly lead to fuel leaks in either the high or low pressure streams.

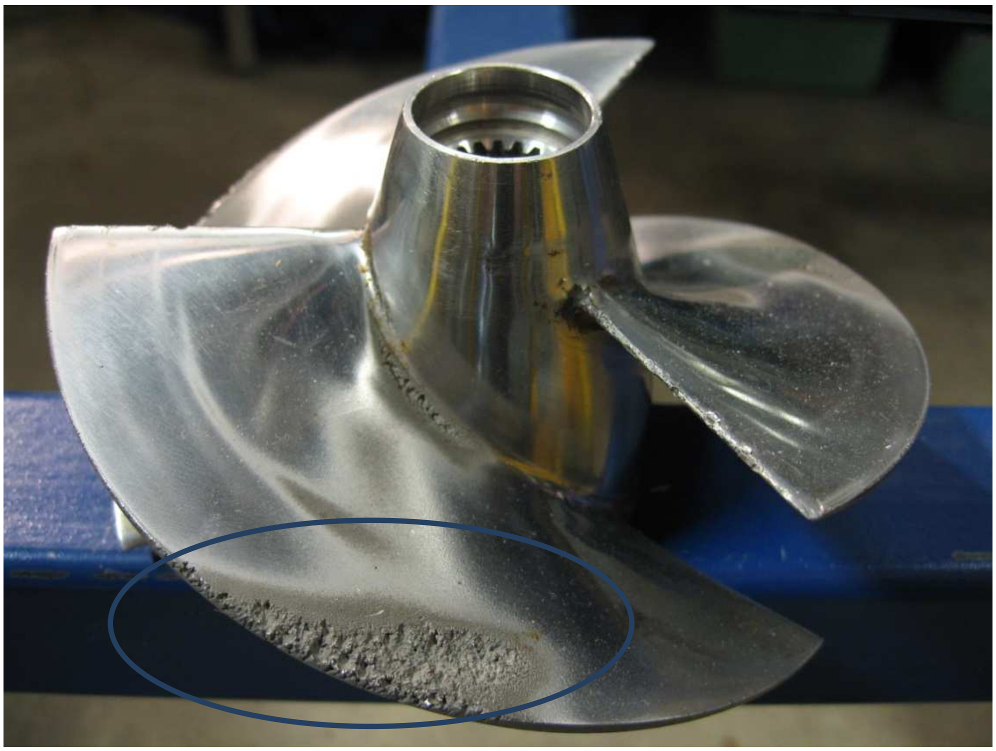


Figure 23: Example of cavitation on a propeller

6.6.4 **Wear on Engine Components**

Many researchers listed in this report have noted the potential for increased wear on fuel injection components due to the lack of lubricity of DME. Many of these research projects involved short term use of DME that resulted in the discovery of fuel pump wear. Hara et al [65] of Izuzu Motors in Japan performed long term testing on various vehicles, each accumulating at least 100,000 km using pure DME. Unlike most other tests of this nature, they performed a complete teardown of the entire engine to determine if DME had caused any detrimental effects on the cylinder head and the crankcase of the engine as well as the usual fuel injection inspections. They concluded that there was very little wear on the fuel pump or the injector needles and a Nitrogen pressure test revealed no leaks in the fuel injection system. However, they did note some early wear on the injector nozzle seat. They also studied the cylinder head and the crankcase and noted some rust deposits and some abrasion on the exhaust valve seat. Unfortunately there was no mention of a "control" engine using pure diesel fuel as a means of comparison for engine wear. Their results are shown in Figure 24 and Figure 25 below:

Fig.17 Photographs of DME engine piston and cylinder head lower face

Figure 24: Pistons and cylinder head after 100,000 km test

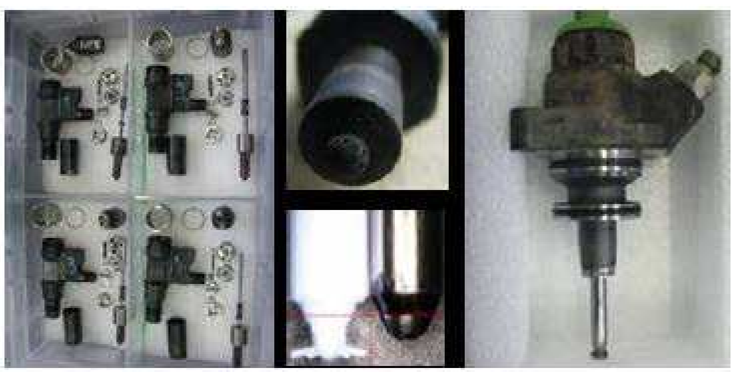


Fig.16 Photographs of DME injectors and supply pump

Figure 25: Fuel injection components after 100,000 km test

6.7 Weights and Dimensions

Operators of most types of heavy duty commercial vehicles must be keenly aware of the weights of their vehicles so that they can calculate the amount of payload that can be added to a vehicle while still respecting the provincial heavy vehicle weight regulations imposed upon them. These regulations not only specify the amount of weight that can be carried by the entire vehicle (gross vehicle weight, GVW) but also the weight over each individual axle (GAW). Therefore, it will be important to understand the effect that changing to DME could have for the entire weight of the vehicle as well as over each individual axle so that operators are not faced with a reduction in payload simply as a result of changing over to a different type of fuel. Additionally, it will be important to maintain the weight distribution over all of the axles so that operators do not have to radically change their loading distribution or move slider axles into positions that affect the performance characteristics of the vehicle.

When considering DME powered vehicles in terms of compliance with provincial vehicle weights and dimension policies it is important to consider comparisons against vehicles fueled with conventional diesel as well as those fueled by CNG and LNG. The comparisons should include the fuel tanks as well as any other additional devices that are either removed, or added, to make a DME vehicle function correctly.

6.7.1 *Fuel Tanks*

Fuel tanks on conventional diesel powered class 8 tractors typically contain between 350 and 550 litres of fuel and weigh between 350 to 550 kg when full of diesel. Some trucks are equipped with one tank whereas many are equipped with twin tanks, one on each side. Twin 378 litre (100 USG) tanks, for example, can yield a range of as much as 1,900 km. These tanks are relatively simple and usually manufactured of thin walled aluminum and are not considered pressure vessels in that the maximum pressure inside the tank is not more than the working pressure of the fuel injection system. Whereas diesel tanks can be filled nearly to capacity, LPG and DME tanks should never be filled to more than 80% of their capacity, by volume, to allow for expansion of the product. [55]

DME tanks can be made to be the same size as those already found on highway tractors, but with only 2/3 the energy density by mass as diesel and a DGE of 1.88, the range of the DME vehicle would be reduced (e.g. 1,010 km vs. 1,900 km above). With a working pressure of approximately 75 psi, the DME tanks are considered pressure vessels but are in the same class as, say, a home barbeque tank. Therefore there are some special handling and storage requirements that must be implemented to ensure the product does not escape or pose a hazard to drivers, refuelers and maintainers but not to the same level as handling CNG tanks (Section 8). DME tanks are generally bracket mounted on the side of the vehicle in the same position as diesel tanks.

Although the engines on CNG and LNG powered vehicles are identical, the fuel storage and delivery systems for each fuel have their own unique requirements that make them different from each other and from conventional diesel or DME powered vehicles. Most CNG tanks operate with a working pressure of approximately 3,600 psi [66] in North America (3,000 psi in Europe). This high pressure requires a very strong pressure vessel that is engineered and manufactured in a particular manner to resist hoop stress and other explosive forces. Most tanks are made of carbon fibre and can weigh 360 kg (~800 lbs) more than a similarly sized DME fuel tank (see Figure 26). Additionally, since CNG has such a low energy density, it is common for the CNG product to be stored in a rack of multiple tanks to maintain vehicle range at acceptable levels. The rack is typically mounted vertically behind the cab whereas LNG tanks tend to be mounted in the same position as diesel tanks, as shown in Figure 27.

The product inside a LNG tank must be maintained in the liquid state at temperatures as low as -160 °C (-260 °F) which is in its cryogenic form but at atmospheric pressure. Therefore, the tanks are typically domed pressure vessels, manufactured from stainless steel and are of double wall construction with a perfect vacuum in between the two shells. The tanks are therefore extremely expensive to produce and can weigh 320 kg (700 lbs) more than a similarly sized DME tank (see Figure 26). Data from JB Hunt Transportation [50] revealed weight increases of up to 454 kg for LNG and as much as 1,100 kg for CNG. According to Cummins Westport, their filled 60 DGE LNG tank weighs 500 kg (1,100 lbs) and their filled 62 DGE CNG tank weighs 727 kg (1,600 lbs). These weights are comparable to the diesel tanks listed above, however, the diesel tanks are all able to hold 100 to 150 gallons of fuel, which would provide considerably more range than the 60 DGE shown for CNG and LNG. The data from Cummins has been compiled in Table 11 to illustrate the potential weights of various vehicles.

Table 11 – Weight estimates for ~60 DGE fuel tanks and SCR

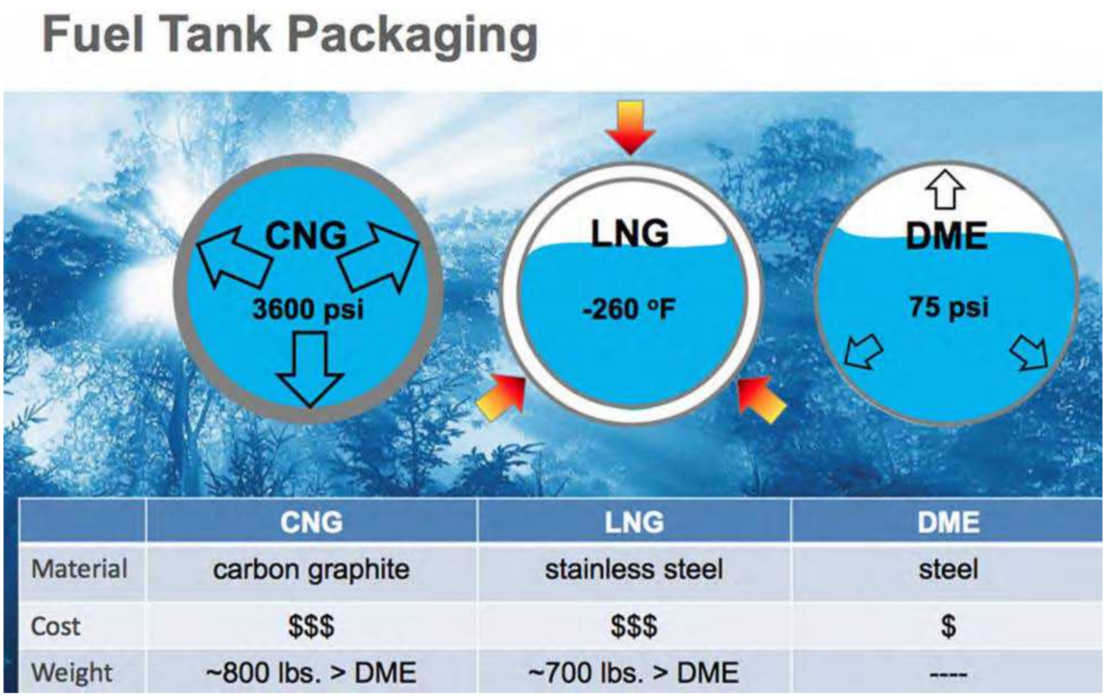
	Diesel	LNG	CNG	DME
Actual Tank Volume	60 gal/226 l	119 gal/450 l	326 gal/1233 l	135 gal/512 l
Usable Tank Volume	60 gal/226 l	102 gal/386 l*	82 DGE	113 gal/427 l*
Diesel Gallon Equivalent	60 DGE/226 l	60 DGE/226 l	62 DGE/234 l	60 DGE/226 l
Dry Tank Weight	30 kg	225 kg	545 kg	75 kg***
Product Weight	199 kg	173 kg	162 kg	282 kg
SCR + Urea	200 kg	0 kg	0 kg	0 or 200 kg
DPF	50 kg	0 kg	0 kg	0 kg
Total	479 kg	398.5 kg	707 kg	357 kg/557 kg**
Increase over Diesel	0 kg	-81 kg	228 kg	-122 kg/78 kg

*LNG and DME tanks can only be filled to 80% of actual volume

** Assuming no DPF but optional SCR

*** Estimate. No actual data found

Type of Tank	**Construction** [67]	**Weight** [67]	**Cost per litre (water volume)** [67]
CNG Type I	All steel	1.4 kg/litre	$5/litre
CNG Type II	Steel or Aluminum with reinforced polymer	1.1 kg/litre	$7.5/litre
CNG Type III	Metal liner with full carbon fiber overlay	0.4 kg/litre	$15/litre
CNG Type IV	Carbon fibre over a thermoplastic liner	0.4 kg/litre	$15/litre
CNG Type V	All carbon fibre	0.3 kg/litre	$20/litre



	CNG	LNG	DME
Material	carbon graphite	stainless steel	steel
Cost	$$$	$$$	$
Weight	~800 lbs. > DME	~700 lbs. > DME	----

Figure 26: Various Fuel Tank Specifications (Volvo group)

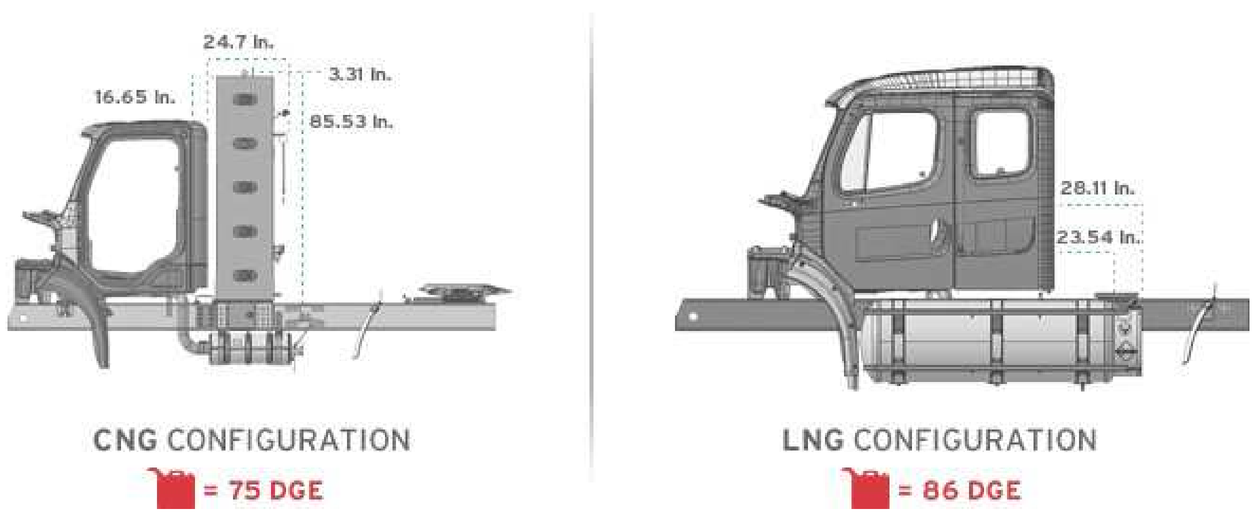


Figure 27: Location of LNG and CNG tanks (courtesy Freightliner Trucks)

TNO in the Netherlands designed a computer simulation program in the late 1990s to determine the increase in tare weight on a city bus for various fuels, including DME. Each of the fuels was then assigned a 'weight penalty' for use on the baseline vehicle relative to the diesel powered vehicle. [68] Their simulation considered not only the tank weight but any incremental increases in weight due to the density of the fuel itself and the increase in volume of fuel required to maintain a reasonable range. Their work revealed that DME powered city buses would be approximately 170 kg heavier than similarly equipped diesel buses. However, it should be noted that this analysis was performed well before the widespread use of SCR and diesel particulate filters which, combined, would add more than 170 kg to the weight of a bus which would likely make the conversion to DME weight-neutral when compared to diesel. The complete results of their work are shown in

Table 12.

The exact tank size and mass will depend on each operator's requirements but it is clear that CNG powered vehicle will generally be heavier than similarly equipped diesel vehicles although the exact value depends on tank size and the weight of the SCR equipment on the diesel powered vehicle. Making absolute comparisons between diesel, CNG, LNG and DME tanks (and hence vehicle weight) is difficult because OEMs and operators design vehicles differently based on range, space and weight requirements. One operator may elect to accept a shorter range for the benefits of a lighter tank whereas other operators may be able to accept a higher tank weight if extended range is critical. The comparisons are made more difficult since LNG, CNG and DME are all stored in different states than diesel and therefore the concept of a diesel equivalent gallon (DGE) must be used for comparisons. Tank weights in general go from diesel at the lighter end of the comparison scale, to DME, to LNG to CNG at the heavier end of the comparison scale.

Table 12 – Results of TNO fuel tank weight penalty study

Fuel Type	Incremental Weight Increase (kg)
Diesel	0
DME	+170
CNG	+700 to +1100
LNG	+100
LPG	+20 to +60
Methanol	+150
Gasoline	-150

6.7.2 *Removal of Emission Control Devices*

The use of DME dictates the need for some upgraded fuel components and a new pressure vessel fuel tank when compared to diesel powered vehicles. All of these additions add weight to the vehicle when compared to diesel vehicles. However, the current Environment Canada (and EPA) regulations have caused all engine manufacturers to add many new components to their engines and exhaust systems as well, all of which add cost and weight to a vehicle. The Navistar group had initially announced they were planning to meet 2010 emission regulations using massive exhaust gas recirculation (EGR) which would have added minimal weight to the vehicle. However, they eventually decided to use the same technology that all other North American manufacturers had elected to use: selective catalytic reduction (see Section 2.2.1). An SCR system on a class 8 tractor has, as a minimum, the following devices: fluid tank, diesel exhaust fluid, heater elements, dosing unit, pipes and hoses and other peripheral items such as clamps and valves. All of these devices can add between 200 to 300 kg to the tare weight of a vehicle. Similarly, diesel particulate filters, traps and oxidation catalysts all add weight to the

exhaust system of a vehicle. A typical class 8 tractor today has at least 50 kg of traps and filters on board to reduce particulate matter emissions.
It is clear that DME powered vehicles will not require particulate filters or traps which will reduce vehicle tare weight by 50 kg to 100 kg. What is less clear, is the relationship between the need for SCR, diesel oxidation catalysts and EGR. Some of the tests referenced in this document illustrated that DME powered vehicles could pass emissions reduction regulations without SCR, however, these results were being compared to regulations that have been superseded by stricter regulations (Euro VI vs. Euro V for example). As NO_x emission limits become lower and lower, the ability for EGR to independently manage NO_x levels without the need for SCR may be compromised. Further testing will be required to determine if DME powered vehicles can pass the current set of emission regulations with light to moderate EGR and a DOC without any detrimental effects on fuel consumption, engine wear or power de-rating. Removing SCR and DPFs has the potential to remove 200 kg to 300 kg of weight from heavy duty vehicles but it is not clear if complete removal of SCR is possible.

NRC-AST compiled all of the weight data for CNG, LNG, LPG, DME and diesel and created an estimate of the combined weight of fuel tanks, the fuel in the tanks as well as any emissions devices such as EGR, SCR or DPF. These data were summed up for all tank sizes between 10 DGE and 150 DGE. As can be seen in Figure 30, the slope for CNG is quite a bit steeper than the other fuels although the total contribution to vehicle mass is actually less than diesel or DME for tanks below about 30 DGE. The weight contribution for DME is shown twice: one for vehicles with SCR and one for vehicles with moderate EGR but no SCR. Unlike diesel, for each of the DME examples, there was no mass included for a DPF. For nearly all tank sizes, DME with SCR represents the second highest vehicle mass, however, DME without SCR is lighter than LNG and diesel for nearly all tank sizes showing how sensitive the calculations are to the addition of SCR.

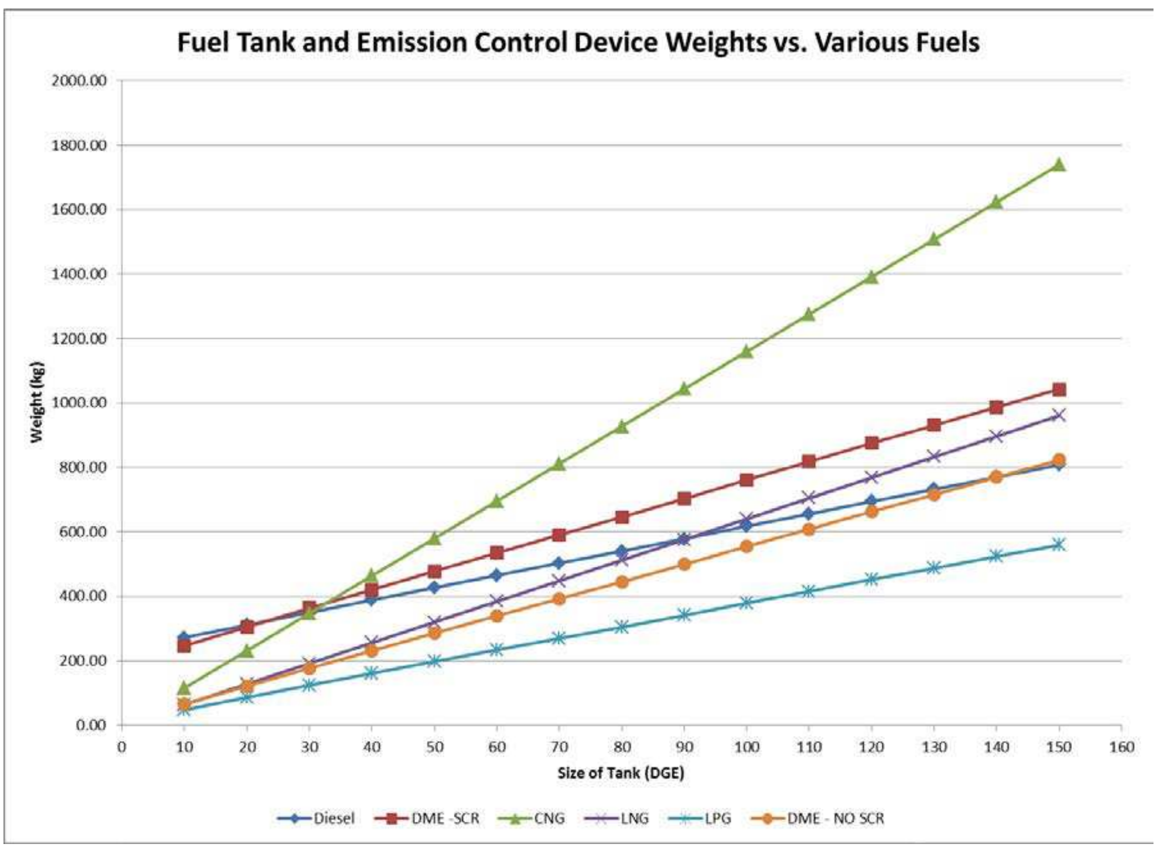


Figure 28: Fuel tank and emission control device weights for various fuels

7 SUPPLY CHAIN AND COMMERCIAL AVAILABILITY

The potential availability of DME and the supply chain required to maintain this availability are presented in this section. The fuel availability, dispensing requirements and potential pitfalls to widespread use of DME for highway use have been compared to other alternative fuels such as CNG and LNG. The availability and dispensing of pump diesel and gasoline are well understood and is considered a commodity and has not been discussed in this section.

7.1 Compressed Natural Gas

North America's largest manufacturer and up-fitter of CNG and LNG engines, Cummins Westport, acknowledges [66] that its CNG and LNG products are mostly aimed at vocational, mining, lighter duty and inner city use due to reasons of fuel supply chain, vehicle range (less than 400 km/day) and available horsepower in the smaller displacement engines. In addition to the Cummins information, some fleet owner user trials have shown in-service ranges as high as 600 km, using twin 45 DGE tanks. [69]

However, compared to conventional diesel, these types of range figures remain one of the more significant factors against widespread use of CNG as there are simply not enough CNG stations along heavy haul transport corridors to guarantee re-fueling. JB Hunt Transportation [50] indicated that finding fueling stations in the correct locations remains the greatest obstacle to their migration to LNG/CNG vehicles. Additionally, time filled CNG pumping stations can take three to six hours to fill [66] making it all but impractical for vehicles that need to refuel during revenue service hours (i.e. a tractor that refuels along highway 401 while en-route to make a delivery). These types of refueling pumps are more suited to vehicles that return to a home base every night and are parked off revenue service for eight hours or more. High pressure "fast-fill" 3,600 psi CNG pumps can deliver fuel to the vehicle at approximately 5 to 8 DGE per minute and are more suited to retail stations where customers demand fill times similar to those of diesel. According to the JB Hunt Transportation white paper, [50] the range of a CNG powered vehicle can be affected by the type of fill rate because fast-fill processes cause an increase in heat due to the speed at which high pressure product is being delivered into the tanks. The lower pressure time-fill process allows for more product to be delivered, with a corresponding increase in range for the same tank size provided the operator is willing to wait for the much slower process.

CNG stations require local zoning for natural gas piping of at least 100 psi high pressure gas lines since all CNG stations are fed from pipelines rather than delivery trucks. This makes CNG use impractical for remote locations unless these locations are fed by pipelines.

The costs to construct and manage a CNG pumping station can vary tremendously depending on the type of station and the number of vehicles that will be served by the station. The American National Renewable Energy Laboratories (NREL) performed an in depth study [70] outlining the costs for fast-fill stations, time-fill stations and combination stations that use both methods. They also made a distinction between publicly accessible fill stations and stations designed primarily for fleet use (be they public transit or private fleets). Most of the information found in the document is too detailed for this report but the estimates of station construction costs have been shown in Table 13. The NREL report did not make mention of electrical costs to operate the stations after commissioning.

Table 13 – Approximate Cost of CNG Filling Stations

Station Capacity/day		Approximate Costs (USD)	
GGE	**DGE**	**Time Fill**	**Fast Fill**
5 to 10	4.4 to 8.8	$5,500 to $10,000	Not applicable
20 to 40	18 to 35	$35,000 to $50,000	$45,000 to $75,000
100 to 200	88 to 176	$250,000 to $500,000	$400,000 to $600,000
500 to 800	440 to 704	$550,000 to $850,000	$700.000 to $900,000
1,500 to 2,000	1320 to 1760	Not applicable	$1.2M to $1.8M

Cummins Westport produced one case study [66] involving a CNG fast fill station with four dedicated lanes sitting on ½ acre of land (see Figure 29) with pump rates as high as 10 usg/min each. They claimed a cost of $5M USD to construct the site but did not explicitly state how many vehicles would be served by this re-fuel site (although the author assumes it is a very large fleet, such as a transit bus fleet). The compressors and pumps demand high electrical current due to the combined 2,500+ hp drive motors and can cost as much as $30,000 USD per month in utility charges (note utility costs per kWh vary to operate on a continuous basis [66]). Cummins claimed these utility costs were more than twice the cost of a comparable LNG station. It is clear that a very strong business case must be made in order to construct and operate a large scale dedicated fast fill CNG fuelling station. For the time being they are most suited to owners of large CNG fleets who want to self-refuel, rather than on the side of a highway where an unpredictable clientele may not support the high investment. As a point of comparison, an urban transit authority such as Ottawa's OC Transpo, with a fleet of more than 900 buses, would typically require between 38,000 litres and 56,000 litres (10,000 and 15,000 US gallons) per day, which is roughly ten times more than what is shown in the highest capacity NREL example in Table 13 and likely more in keeping with the estimates provided by Cummins.

Figure 29: Example of a privately owned CNG filling station

The Canadian Natural Gas Vehicle Alliance (CNGVA) lists all the CNG stations that are currently available in Canada and estimates a current population of 36 public stations and 44 privately owned stations. [71] The distribution of the stations, by province, is shown in Table 14. The website 'gowithnaturalgas.ca' [72] claims there are 41 public refueling stations in Canada but provides a link to the CNGVA site for the exact census data.

Table 14 – Location of CNG Canadian stations

Province	Public (#)	Private (#)	Total (#)
British Columbia	11	20	31
Alberta	11	4	15
Saskatchewan	7	0	7
Manitoba	0	0	0
Ontario	5	17	22
Quebec	2	3	5
Maritime Provinces	0	0	0
Territories	0	0	0
Total	**36**	**44**	**78**

No special training or protective equipment is required in order to use a CNG station, although operators must receive familiarization training to understand the various fittings and filling procedures. As an example, TC-etv2 has recently partnered with NRC-AST to install a CNG fast-fill station at the NRC Uplands campus. The construction of the facility required a natural gas line, security fencing and safety devices such as shut off valves and fire extinguishers. Staff using the fast fill station need only to have had a one hour familiarization training session to understand the safe procedure for dispensing CNG into test vehicles.

7.2 Liquefied Natural Gas

Cummins also states that LNG powered vehicles can have ranges of more than 400 km/day [66] and that the fuel can be dispensed into the vehicle at a rate of more than 15 DGE per minute which is significantly faster than CNG (and less LNG is required than CNG for the equivalent amount of energy). The method of delivery is typically pipeline gas that must be cooled via liquefaction to -160 °C (-260 °F) and is then delivered to the fuel stations via cryogenic tanker trailers. LNG is therefore more practical for remote locations since it can be transported over long distances without degrading the product. The fuel is then stored on site (see Figure 30) in large cryogenic tanks and has a shelf life of approximately five to seven days before it becomes too warm to be used and is vented from the tanks. This means that operators must be very confident they will dispense the fuel in time, making this a very risky business prospect along public roadways where public consumption and perception can vary depending on a number of factors that cannot be controlled by the refuelling station owner. Additionally, it is not ideal for LNG to be stored in tanks that are exposed to high heat from solar radiation during summer months as boil off and venting may occur. These issues are more significant in the southern United States but they must be considered nonetheless. There are still significant infrastructure costs involved with building a LNG station but they are significantly lower than those of CNG and the monthly utility costs are much lower than those of CNG filling (costs were not quantified by Cummins [66]).

Figure 30: Example of a LNG filling station

There is some discrepancy regarding the number of LNG stations in Canada. The Canadian Natural Gas Vehicle Alliance (CNGVA) website [71] states that only two LNG refuelling stations are currently located in Canada, both in British Columbia. According to Cummins Westport, there are eight planned public LNG stations to be built in Canada between 2013 and 2015. [66] A recent presentation by the CNGVA, however, indicates that there may be as many as 17 LNG stations in Canada, 11 in the West and 6 in the East. [73] For example, an article found at “Fleets and Fuels” website [74] indicates that Canada’s first public LNG station opened in spring of 2013, on the Queen Elizabeth highway in Calgary. They go on to state that similar stations would be opening throughout Alberta and Ontario in 2014, 2015 and 2016.

Despite the challenges of building and operating LNG and CNG fueling stations, the product itself is readily available and considered very mature. Therefore, the raw supply is able to meet the demand and there will likely be a ready supply for decades to come based on current natural gas projections.

7.3 DME

There are numerous ways in which DME can be produced and distributed. At the time of report preparation there were no known DME stations in Canada and most of the DME facilities were located in China and Japan with some production also in Denmark. According to a study performed by TNO in 1997, the annual worldwide production of DME was less than 150,000 tons and was used almost exclusively for propellants [68]. The current estimated yearly production of DME is approximately 5 million to 9 million tons, depending on the cited source. [25] [75]. Potential sites being developed include Trinidad and Tobago, North America, Egypt, India, Iran, Indonesia and Uzbekistan. [75] [25] China’s National Development and Reform Commission forecasts 20 million tons of DME production capacity by the year 2020. [25] A few examples are shown in the following sections, including the world’s first bioDME plant in Sweden (Section 7.3.2).

7.3.1 General Production

According to the Natural Resources Canada Fuel Efficiency Benchmarking website [62] there were approximately 240,000 on road highway tractors in Canada in 2012. The average distanced they travelled was 146,000 km and their average fuel consumption was 40 litres/100 km. Using these figures it is possible to estimate that approximately 14 billion litres of fuel was burned for highway class 8 tractors alone. This does not include the fuel required for straight trucks, vocational vehicles and buses.

As presented in this study, DME has many qualities that could allow it to be used effectively as an on road fuel for vehicles that are modified to accept DME (See Section 6.1). However, these qualities cannot be realised if the fuel cannot be delivered to operators in large enough quantities to satisfy the demand. Not only will there be extremely high volumetric demands, but DME’s energy density is lower than conventional diesel meaning that more product will be required, per kilometer, than diesel. Additionally, since highway tractors are often thousands of kilometers away from their home base, it is not sufficient to have a local supply of DME if widespread adoption is desired. In order for DME to be an effective solution for heavy haul transport, refuelling stations will need to be setup at key locations along major transport corridors such as the Trans-Canada Highway and Highway 401 in Ontario, for example. Otherwise, DME will be relegated for use on vocational vehicles, urban transit buses and class 7/8 day cabs that are rarely more than, say, 100 km from their home base.

Cummins Westport [66] estimates that approximately 150 LNG stations would be required throughout the entire US interstate network, at approximately 300 mile intervals, to satisfy the national demand. This, however, includes but one style of highway and does not consider the entire network. It will be important to make such estimates for DME to determine what would be the minimum level of fuel station infrastructure density that could support nationwide use, or at least along the Trans-Canada highway. DME powered vehicles will have fuel systems that are unique compared to any other type of vehicle and will therefore be extremely sensitive to fuel station locations since the vehicle can no longer be operated on any fuel, other than DME, once the conversion is made, unless a completely redundant fuel system is carried on board, which is not a practical option. Unless large fuel tanks are attached to the vehicle, the lower energy density of DME will also make these vehicles sensitive to filling station location since more DME is required per injection pulse compared to diesel meaning that range will be necessarily shorter.

Because the vapor pressure of DME is lower than that of propane at any given temperature, DME can be stored and transported using existing propane facilities [23]. Therefore, DME pumping stations, in theory, could look very similar to stations that currently dispense LPG such as propane for residential barbeques. For this reason, the training requirements for DME station personnel should be similar to those of LPG. Operators will have to be trained in regard to handling pressurized equipment, how to deal with leaks and become familiar with the fittings and filling procedures. As with handling LPG, personal protective equipment (PPE) other than glasses, safety boots and gloves should not be required for DME station attendants. An example of a DME fill port on a class 8 tractor is shown in Figure 31.

Figure 31: Example of DME fill port on class 8 tractor (Volvo group)

7.3.2 **Haldor Topsoe**

Haldor Topsoe is an energy company with head offices in Denmark as well as branch offices worldwide next to sources of raw materials and fossil fuel reserves (e.g. Edmonton in Canada). For nearly 25 years Topsoe has been researching DME production and synthesis. [68] Their initial research focused on the use of DME as an intermediary for other products and processes but recently they have focussed more effort into the development of DME for use as an alternative for diesel powered vehicles.

7.3.3 **Lurgi's MegaDME Process**

Lurgi in Frankfurt am Main, Germany has also created a well documented DME process called 'MegaDME'. At the 2005 Gastech conference in Bilbao, Spain they presented not only the chemical process but a rudimentary economic assessment of the production of DME as a transportation fuel. [76] They highlighted how they had studied two methods of DME generation: co-generation with methanol and dehydration of methanol. They concluded that the co-generation method had too many disadvantages of trying to separate DME from the synthesis loop while the dehydration method simply required the addition of a DME loop to their existing 'MegaMethanol' chemical process in order to produce DME suitable for commercial use. A brief economic study of the production of 99.2% pure DME was as follows, which the authors acknowledge is accurate to within +/- 20%:

Table 15 – Estimate costs for MegaDME process

DME Capacity	5,000 t/day
Natural Gas Demand	28.5 MMBtu/t for Methanol 40.2 MMBtu/t for DME
Total Fixed Costs	$415 MM USD
Cost of Production	$ 93 US/t DME

The final value of $93 US for a tonne of DME represents a production cost and not a commercial cost. This is but one example of production costs and many other more current examples would be required to formulate conclusions relative to other forms of fuel production.

7.3.4 **Volvo/Chemrec BioDME Study**

As discussed in Section 3.1, a major initiative in Sweden called the BioDME [1] project involving Volvo trucks and Chemrec provided one of the most comprehensive pilot projects regarding the production, distribution and use of DME. The details of the industrial DME production are described in Section 3.1 and are not shown again here. This study was meant to replicate a small fleet of revenue carrying vehicles. In order to produce the required amount of DME, a new plant was constructed. The cost of the production plant was 20 million Euros (~$40M CD) and required 10,000 m of pipe and occupied a land area of approximately 600 m^2.

The Chemrec facility, in the northern Swedish city of Piteǻ, combined its daily black liquor by-product with coniferous tree needles and branches and other bio-waste to generate enough DME to power 10 class 8 tractors for a period of two years. The plant was setup using processes and procedures that had been developed by Topsoe (previous section) in the early 90s. On average, the plant produced 4.3 tonnes of DME every day by using only about 1% of its total black liquor stores. In other words, if all of the black liquor had been used and if the plant were expanded to handle all of the black liquor, it is possible that the plant could have produced a total of 430 tonnes of DME every day (or 156,950 t every year) which could conceivably power more than 2,000 tractors for an entire year. Using the NRCan data presented above, approximately 120 such black liquor operations would be required to fuel all 240,000 tractors in Canada every year. Volvo claims that 20 such plants currently exist in Sweden, meaning that a significant percentage of the heavy vehicles in Sweden could be powered exclusively by DME if all of the black liquor from all 20 plants were converted to DME [1].

The DME that was produced by the Chemrec plant in Northern Sweden was then transferred to four different filling stations to provide a re-fuelling network along heavily travelled routes for the ten test trucks. The filling stations were all existing LPG stations and each one required an investment of approximately 200,000 Euros (~$400,000 CND) for the conversion process. [77] The four stations were located in Pitea in the North (65° latitude), and Stockholm, Goteborg and Jonkoping in the South (57.8° latitude). The test team claimed to achieve a filling rate of 49 litres per minute of DME into the test vehicles which is similar, if not even higher, than a conventional gasoline or diesel fuel pump.

The vehicles used for the test program were typical trucks, loaded to full capacity and hauling actual consumer cargo, some loads being as heavy as 60t. The vehicles were equipped with 12.8 litre 6 cylinder diesel engines rated at 440 hp with a compression ratio of 15.9 to 1. The tests were run throughout all four seasons and did not stop for Sweden's cold winter temperatures. The test vehicles accumulated a total of 828,000 km with one vehicle accumulating over 183,000 km [1] . The technical paper [1] developed to describe the project was extraordinarily detailed regarding the production of the DME but was rather limited in its description of the in service trials involving the ten vehicles therefore any information regarding delivery, storage and pumping of the fuel is sketchy.

The results of the testing, including the filling stations, were so encouraging, that on June 6, 2013 Volvo announced it will begin production of DME powered vehicles for the North American market for the 2015 model year. In October 2014 Volvo announced modifications to their DME plans and will continue to study alternative fuels in greater depth throughout 2015, including customer field tests using DME powered Volvo tractors. [78]

Volvo's sister line of vehicles, Mack Truck, has also announced plans to introduce DME to their lineup of vehicles for 2015.

7.3.5 The Oberon Process

Oberon Fuels in Brawley, CA, has developed a unique and proprietary fashion in which they manufacture, ship and distribute DME stations to their customers. They manufacture skid mounted small scale production units that convert methane and carbon dioxide to DME from feedstocks such as biogas and natural gas. These skids are meant to replace large scale infrastructure projects that could cost hundreds of thousands of dollars. The units can produce between 3,000 and 10,000 gallons of DME a day (11,340 litres to 37,800 litres). As a point of comparison, the Volvo/Chemrec study claimed a daily production rate of 4.3 t which corresponds to approximately 6,500 litres of DME.

The Oberon process is ideally suited to regional haulers with large fleets who see each of their vehicles daily and want to reduce costs by not only self fueling, but self-producing the fuel. All of their three fuel production models require at least 40,000 ft^2 (i.e. ~200 ft x ~200 ft) of free space to operate (see Figure 32). The units are also ideal for setting up refueling stations at, say, a mine where local infrastructure cannot support the installation of a DME refueling station.

Figure 32: An Oberon DME installation

7.4 Consumer Cost of DME

The consumer cost of a litre of DME is extremely difficult to quantify at this time for a variety of reasons, most notably, because DME can be produced in many different ways, and from different base stocks (see Section 3.1). The International DME Association, based in Washington, DC, claims that the price of DME is a function of the price of LPG and methanol, for DME produced from methanol. They state that the consumer cost of DME is roughly 75% to 90% that of LPG. They also noted that pure LPG prices fluctuate more since LPG is a petroleum based fuel and must follow global petroleum pricing. DME is a manufactured renewable fuel and, as such, is less sensitive to these global price fluctuations. Oberon, the largest producer of DME in the United States simply states that DME is "competitive with diesel prices" but does not list a consumer cost on their website. [79] [80] The costs shown for the Lurgi process are more than ten years old and for the production of DME and therefore not the consumer cost and are thus very low and cannot be compared to pump diesel prices.

8 ENVIRONMENTAL CONSIDERATIONS

Of all the 70+ research documents that were considered, only one had any useful information relating to cold weather operations. The joint Volvo and Chemrec [1] two year DME project, described in various sections above, was a two year project that operated continuously throughout all of Sweden's four seasons, including their cold winter months. Some of the operations were conducted as far north as the 65th parallel which runs through all three Canadian territories. The test team did not report any operational issues related to ice, snow or cold temperatures. It is not known if Sweden uses salt on their roads to the same extent that is used in some Canadian provinces.

One of the side effects of fuel cell powered vehicles is the amount of product water that is expelled from the tailpipe onto the road surface. [81] In Southern climates this water vapour and liquid simply evaporates in time and does not pose a risk to motorists. However, in Northern climates, this water can freeze on the road surface thus posing a hazard to following motorists. DME produces more water than diesel (Section 3.2.6.4) but not orders of magnitude more (as is the case with fuel cells) therefore it is assumed that the incremental effect to road surfaces would be minimal, when compared to diesel. Additionally, fuel cell product water is emitted as a liquid whereas DME water is typically emitted as a vapour.

One reference did note that some testing demonstrated that DME powered vehicles could start, unassisted, at -24 °C [55] but the source document for that testing was not found. Startability will be a crucial issue for fleets whose vehicles remain parked outside overnight during Canada's winter months, particularly in the North.

Some road vehicle studies performed in Korea and Japan do not adequately address the effects that could be encountered in Canada's climate, however, Sweden's climate is very similar to that of Canada therefore if their experiences are any indication, DME is a fuel that can be used throughout Canada's four seasons.

Still, some cautionary notes were discovered relating to the use of DME in regions of the world where cold temperatures and road salt are prevalent. Most notably they include:

- Threaded fasteners and bracketry used to attach DME fuel system components should be corrosion (salt/oxidation) resistant; [37]
- The vehicle's DME fuel tank should be corrosion (salt/oxidation) resistant and positioned such that it is not subjected to road sand/salt/water. [37]
- Rigorous yearly inspections may be required to ensure that fuel tank integrity has not been compromised due to corrosion. DME tanks are pressure vessels and are therefore more rugged than conventional diesel tanks thus the risk of tank failure is actually lower. However, the consequences of a tank failure are potentially more severe since it is a pressurized gas that could be expelled at high velocity;

9 SAFETY CONSIDERATIONS

9.1 Codes and Standards

Until recently, DME for use in engines was essentially an unregulated industry due to a lack of widespread use. However, new standards are now being implemented to guide the industry in the development of DME as it pertains to vehicle use.

On September 3rd, 2014 DME achieved an important status as a transportation fuel in the United States when the EPA confirmed [82] that DME produced from bio-gas and other renewable sources qualified for inclusion under the Renewable Fuel Standard (RFS). This follows the announcement in February of 2014 outlining the new ASTM standard for DME: ASTM D7901: "*Standard Specification for Dimethyl Ether for Fuel Purposes*". [83] The standard provides guidelines for fuel producers, vehicles manufacturers, component suppliers and re-fuellers with the information required to determine DME purity, testing, safety and handling. Although the ASTM standard was developed in the USA, it is expected that the standard will be adopted in Canada as well.

Teng et al. theorized that DME and LPG are sufficiently similar that the (US) Department of Transportation (DOT) specifications for the propane tank containers may be applied directly in the design of the DME fuel tanks [23].

The International Standards Organization (ISO) is currently drafting a series of ISO standards relating to the testing, production and handling of DME. Some of these standards include:

- ISO 17196: *2014 Dimethyl Ether for Fuels - Determination of Impurities- Gas Chromatographic Method*. [1]
- ISO/FDIS 16861. (2013). Petroleum products—Fuels (class F)—Specifications of Dimethyl ether (DME). [1]
- ISO/FDIS 17197. (2013). Dimethyl ether (DME) for fuels—Determination of water content—Karl Fischer titration method. [1]
- ISO/FDIS 17196. (2013). Dimethyl ether (DME) for fuels—Determination of impurities—Gas chromatographic methodISO/FDIS 17198. (2013). Dimethyl ether (DME) for fuels—Determination of total sulfur, ultraviolet fluorescence method. [1]
- ISO/FDIS 17786. (2013). Dimethyl ether (DME) for fuels—Determination of evaporation residues—Mass analysis method. [1]

The standard valve connections are regulated in the USA and Canada by the compressed gas association CGA-510.

In Canada, Transport Canada Dangerous Goods division determines **[84]** what type of dangerous goods placard must be displayed on fuel delivery vehicles containing products such as DME. A placard similar to LPG (UN #1075) will be required for DME transportation and will bear the number 1033, as shown in Table 16. Note this is for bulk transportation of DME and not for vehicles that simply use DME as a fuel.

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Table 16 – Dangerous Goods Classification

TDG Proper Shipping Name	Dimethyl ether
Hazard Class	2.1
UN-No	UN1033
Description	UN1033, DIMETHYL ETHER,2.1

9.2 Potential Hazards Associated with the Use of DME

There are a variety of safety precautions that must be taken when manufacturing, transporting and re-fueling DME. In addition, there are some DME specific features that operators and maintainers must be aware of when servicing vehicles. Some of the precautions are similar to those of propane and other forms of LPG whereas others are DME specific. Teng at al theorized that DME tends to be safer than gasoline for three reasons. [23]

- DME is stored in a pressurized tank and thus it is not exposed to air;
- The auto ignition temperature of DME is close to that of gasoline (≈ 350°C) but DME must be present in a 5.7 times greater concentration than gasoline to ignite when DME is exposed to air;
- DME exposed to air disperses more rapidly than gasoline due to having a much smaller molecular weight than that of gasoline (~46 vs ~100) thus any possible leak from the DME fuel system would be diluted more rapidly.

9.2.1 *Carcinogenicity*

Studies have revealed that DME is not a known carcinogen. [55]

9.2.2 *Soil Contamination*

Unlike diesel fuel, DME is contained within a pressure vessel and remains a vapour at temperatures above -25 °C therefore leaks would typically vapourize into the atmosphere and not drip below and contaminate soil or water. [55]

9.2.3 *Parking in Underground Garages*

Like propane/LPG, DME is heavier than air in the vapour state (1.993 kg/m^3 vs. 1.275 kg/m^3 at STP) and 1 litre of liquid DME will vapourize to produce 374 litres of gas (at standard temperature and pressure). [55] Therefore, DME powered vehicles should not be parked for extended periods of time in underground parking garages or other areas where oxygen could be displaced by leaking DME vapours. The displacement of oxygen by DME could cause suffocation to humans and animals. Additionally, since DME is a combustible material, there is a risk of explosion if a source of open flame is thrown on the ground where DME could be pooling. The NRC has recently delivered a report to Transport Canada [85] outlining the results of a computational fluids dynamic (CFD) study that attempted to predict the flow and dispersion of CNG in parking garages. The details of that report are outside the scope of this report but it would be useful to perform a similar study to determine if the characteristics of DME would be similar to those of CNG with respect to pooling and dispersion.

9.2.4 *Material Safety Data Sheet Information*

The Material Safety Data Sheets (MSDS) for DME from Praxair [86] and Linde, [87] two well known gas supply companies, were reviewed in order to fully understand the health risks involved with the use of DME. The MSDS lists the following areas for concern under the heading of 'Emergency Overview':

- Extremely flammable;
- May cause skin and eye irritation;
- Causes central nervous system depression;
- Contact with product can cause frostbite;
- Contents under pressure;
- Keep at temperatures below 52 °C;
- Colourless appearance;
- Compressed gas;
- Odor: Ether;

Table 17 illustrates the potential health risks of DME.

Table 17 – Potential Health Effects of DME (MSDS)

Item	Health Effect
Principal Routes of Exposure	Inhalation. Eye contact. Skin contact
Acute Toxicity	None
Inhalation	May cause central nervous system depression with nausea, headache, dizziness, vomiting, and incoordination.
Eyes	This product is a gas at room temperature. Contact with liquid may cause frostbite. May cause irritation
Skin	This product is a gas at room temperature. Contact with liquid may cause frostbite. May cause irritation
Skin Absorption Hazard	No known hazard in contact with skin.
Ingestion	Not an expected route of exposure
Chronic Effects	No known effect based on information supplied
Aggravated Medical Conditions	Skin disorders. Central nervous system. Respiratory disorders.
Environmental Hazard	See Section 12 for additional Ecological Information.

Table 18 lists the first air measures that are required after contact with DME, according to the Linde MSDS. [87] The required measures for propane are also included as a comparable. Many of the first aid measures are similar, however, the attention that must be given for inhalation appears to be more involved for DME than for propane.

Table 18 – First Aid Measures

Item	**First Aid Measure DME**	**First Aid Measure Propane**
Eye Contact	None required for gas. If frostbite is suspected, flush eyes with cool water for 15 minutes and obtain immediate medical attention	Rinse opened eye for at least 15 minutes under running water. Then consult a doctor.
Skin Contact	None required for gas. For dermal contact or suspected frostbite, remove contaminated clothing and flush affected areas with lukewarm water. DO NOT USE HOT WATER. A physician should see the patient promptly if contact with the product has resulted in blistering of the dermal surface or in deep tissue freezing	Generally the product does not irritate the skin.
Inhalation	PROMPT MEDICAL ATTENTION IS MANDATORY IN ALL CASES OF INHALATION OVEREXPOSURE. RESCUE PERSONNEL SHOULD BE EQUIPPED WITH SELF-CONTAINED BREATHING APPARATUS. Conscious inhalation victims should be assisted to an uncontaminated area and inhale fresh air. If breathing is difficult, administer oxygen. Unconscious persons should be moved to an uncontaminated area and, as necessary, given artificial resuscitation and supplemental oxygen. Treatment should be symptomatic and supportive	Remove person to fresh air. If breathing is difficult or has stopped, administer artificial respiration. Obtain immediate medical attention.
Ingestion	None under normal use. Get medical attention if symptoms occur.	Not an applicable.
Notes to Physician	Treat symptomatically.	NA

The accidental release measures are shown in Table 19. [86] [87]

Table 19 – Accidental Release Measures (MSDS)

Item	Accidental Release Measure
Personal Precautions	ELIMINATE all ignition sources (no smoking, flares, sparks or flames in immediate area). Evacuate personnel to safe areas. Keep people away from and upwind of spill/leak. All equipment used when handling the product must be grounded. Wear self-contained breathing apparatus when entering area unless atmosphere is proved to be safe. Monitor oxygen level.
Environmental Precautions B	Beware of vapors accumulating to form explosive concentrations. Vapors can accumulate in low areas. Use water spray to reduce vapors or divert vapor cloud drift. Avoid allowing water runoff to contact spilled material. Prevent spreading of vapors through sewers, ventilation systems and confined areas.
Methods for Containment	Stop the flow of gas or remove cylinder to outdoor location if this can be done without risk. If leak is in container or container valve, contact the appropriate emergency telephone number in Section 1 or call distributor
Methods for Cleaning Up	Return cylinder to authorized distributor.

The handling and storage measures are shown in Table 20. [86] [87]

Table 20 – Handling and Storage (MSDS)

Item	Measure
Handling	Ground and bond all lines and equipment associated with product system. All equipment should be non-sparking and explosion proof. "NO SMOKING" signs should be posted in storage and use areas. Remove all sources of ignition. Use only in ventilated areas. Never attempt to lift a cylinder by its valve protection cap. Protect cylinders from physical damage; do not drag, roll, slide or drop. When moving cylinders, even for short distance, use a cart designed to transport cylinders. Use equipment rated for cylinder pressure. Use backflow preventive device in piping. Never insert an object (e.g. wrench, screwdriver, pry bar, etc.) into valve cap openings. Doing so may damage valve, causing leak to occur. Use

	an adjustable strap wrench to remove over-tight or rusted caps. Close valve after each use and when empty. If user experiences any difficulty operating cylinder valve discontinue use and contact supplier. Never put cylinders into trunks of cars or unventilated areas of passenger vehicles. Never attempt to refill a compressed gas cylinder without the owner's written consent. Never strike an arc on a compressed gas cylinder or make a cylinder a part of an electrical circuit.
Storage	Separate dimethyl ether cylinders from oxygen, chlorine and other oxidizers by at least 20 feet or use a barricade of non-combustible material. This barricade should be at least 5 feet high and have a fire resistance rating of at least 1/2 hour. Outside or detached storage is preferred. Protect from physical damage. Cylinders should be stored upright with valve protection cap in place and firmly secured to prevent falling. Store in cool, dry, well-ventilated area of non-combustible construction away from heavily trafficked areas and emergency exits. Keep at temperatures below 52°C / 125°F. Full and empty cylinders should be segregated. Use a "first in-first out" inventory system to prevent full cylinders from being stored for excessive periods of time. Always store and handle compressed gas cylinders in accordance with Compressed Gas Association, pamphlet CGA-P1, Safe Handling of Compressed Gases in Containers.

The exposure controls are shown in Table 21. [86] [87]

Table 21 – Exposure controls (MSDS)

Item	Measure
Exposure guidelines	This product does not contain any hazardous materials with occupational exposure limits established by the region specific regulatory bodies
Engineering measures	Explosion proof ventilation systems. Local exhaust ventilation to prevent accumulation of high concentrations and maintain air-oxygen levels at or above 19.5%.
Ventilation	Ensure adequate ventilation, especially in confined areas

9.2.5 *Personal Protective Equipment*

MSDS sheets for DME from various gas suppliers [86] [87] confirm that some protective equipment is suggested for use when handling DME. The following equipment should be worn:

- Eye protection should be worn if splashes are likely to occur;
- Wear cold insulating gloves when handling liquid. Safety shoes. Appropriate protective and chemical resistant gloves, clothing and splash protection, or fully encapsulating vapor protective clothing to prevent exposure. For materials of construction consult protective clothing manufacturer's specifications;
- No special respiratory equipment is required under normal circumstances. Use positive pressure airline respirator with escape cylinder or self-contained breathing apparatus for oxygen-deficient atmospheres (<19.5%).

Some specific references to current CSA documents were shown, as follows:

- Respiratory protection in accordance with Canadian Standards Association (CSA) Z94.4 "*Selection, care and use of respirators*" should be donned when working in a confined space;
- CSA Z94.3 applies to the use of eye-ware when handling pressurized cylinders; and
- CSA Z195 applies to protective foot wear for personnel handling pressurized cylinders.

9.2.6 *Emergency Services and First Responders*

When new vehicles or new fuels are introduced it is critical that first responders have the tools, equipment, personal protective equipment (PPE) and knowledge required to not only save the lives of accident victims, but to protect themselves from the hazards that are present at the incident scene. The firefighting measures are shown in Table 22.

Table 22 – Firefighting measures for DME (MSDS)

Item	**Firefighting Measure**
Flammable Properties	Extremely flammable.
Extinguishing Media	Dry chemical or CO_2. Water spray or fog. DO NOT EXTINGUISH A LEAKING GAS FIRE UNLESS LEAK CAN BE STOPPED
Hazardous Combustion Products	Carbon monoxide. Carbon dioxide (CO_2).
Sensitivity to Mechanical Impact	None
Sensitivity to Static Disharge	Yes
Specific Hazards Arising from Chemical	Will form explosive mixtures with air. May form explosive mixtures in presence of oxidizing substances (gas/dust) Continue to cool fire

	exposed cylinders until flames are extinguished. Cylinders may rupture under extreme heat. Damaged cylinders should be handled only by specialists.
Precautions for firefighters.	If possible, stop the flow of gas. Do not extinguish the fire until supply is shut off as otherwise an explosive-ignition may occur. If the fire is extinguished and the flow of gas continues, use increased ventilation to prevent build-up of explosive atmosphere. Ventilation fans must be explosion proof. Use non-sparking tools to close container valves. Isolate spill or leak area for at least 100 meters (330 feet) in all directions. Vapors from liquefied gas are initially heavier than air and spread along ground. Vapors may accumulate in confined areas (basement, tanks, hopper/tank cars, etc.). Vapors may travel to source of ignition and flash back. For massive fire, use unmanned hose holders or monitor nozzles; if this is impossible withdraw from area and let fire burn. Use water spray to cool surrounding containers. Be cautious of a Boiling Liquid Evaporating Vapor Explosion, BLEVE, if flame is impinging on surrounding containers. As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

9.3 Explosion and Detonation Characteristics

Many references have been made to similarities between DME and LPG throughout this report. The similarities and differences with regards to explosion, detonation and containment should also be investigated, particularly for a DME and air environment, rather than the more theoretical air and oxygen combination. [88] Mogi et al [88] performed a series of experiments comparing the explosion and detonation characteristics of propane and DME. They created three types of tank enclosures: a 180 litre spherical tank, a 22 litre barrel and a 4 litre spherical tank. They recorded the maximum pressure of induced explosions from DME and propane. The differences in maximum measured pressure ranged from 4% higher to 7.8% higher for DME when compared to LPG, depending on which container was considered. Their study was preliminary and did not represent the types of pumps and vessels that would be found at a filling station. In a separate study, Mogi et al [89] attempted to create more realistic explosion scenarios that could be encountered at a pumping station. They theorized that DME pumping stations would be constructed in Japan in the near term and safety issues would need to be understood. One of the main scenarios they investigated was as follows:

- A driver connects a DME hose to the vehicle tank;
- The driver connects a safety coupling to the supply hose;

- The driver refuels but then drives the vehicle away without de-coupling which causes a rupture in the hose or the coupling;
- The leaking DME is then ignited by a spark or an electrostatic discharge;
- A DME vapour cloud is then released;
- The vapour cloud then explodes.

As a result of this hypothesis, they simulated a rapid and large scale leak as a result of a fuel hose break and attempted to quantify the dispersion and explosion behaviours as well as measuring the overpressure and heat flux from the fireball. They concluded that the duration of the fireball decreased as the distance between the nozzle and the ignition point increased because the burning velocity was lower than the jet velocity. Unfortunately the study was highly specialized and very specific to flame science and did not ultimately provide specific information regarding how the results would affect the design and safety procedures at a filling station. The results of some of the tests are shown in Figure 33. Ideally, a study comparing explosions and fireballs from DME and propane at North American style refuelling stations would be more useful since propane stations have been in operation in North America for decades and the safety procedures at these stations are mature and well understood. Ultimately it will be useful to understand if DME stations can be treated the same way as LPG stations with regards to explosions and fires.

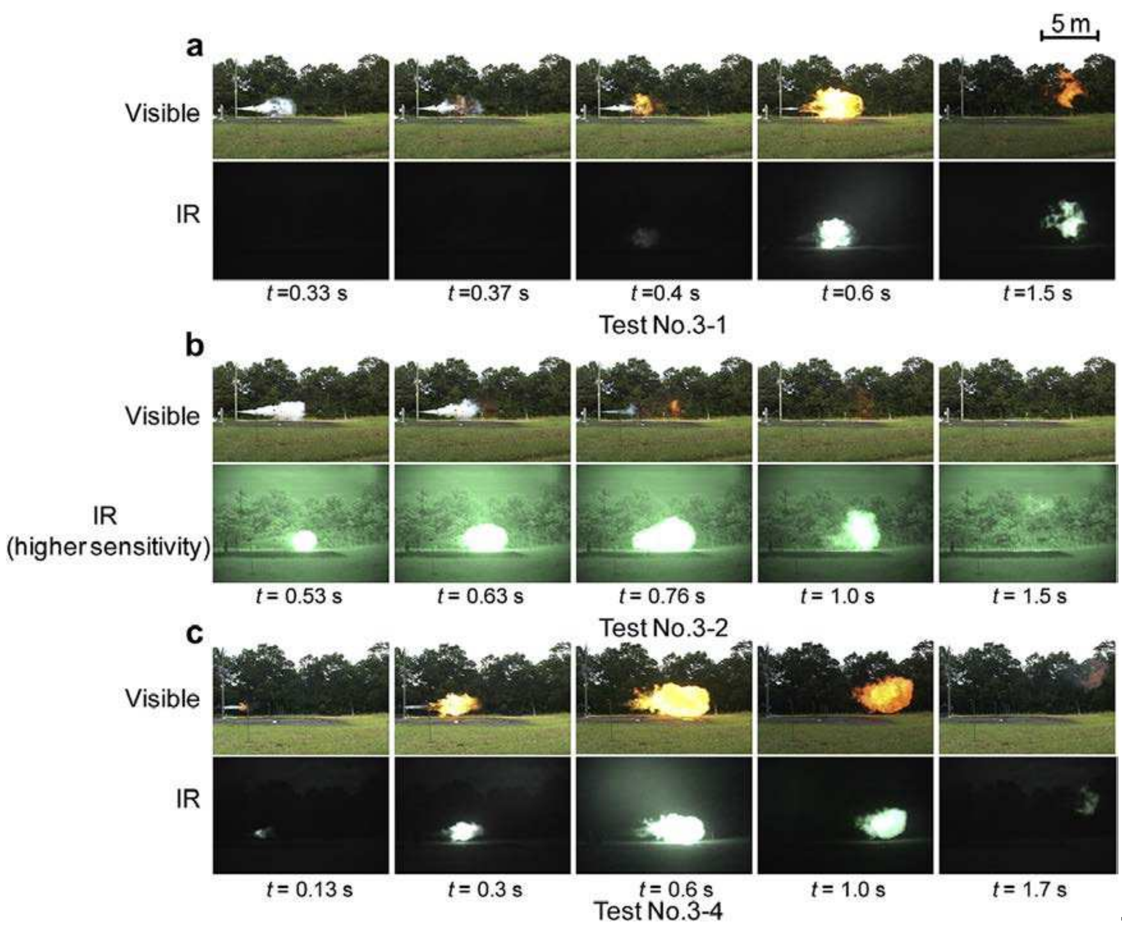

Figure 33: Simulated DME filling station explosions

9.4 Additional Training Required for Operators or Maintenance Personnel

As with any new vehicle, training will be required for operators and maintainers who are not familiar with the distinguishing features of DME. All of the safety procedures have been outlined in the previous sections. All of the protective equipment listed in those tables will be required by operators, maintainers and first responders who come into contact with DME powered vehicles. From the driver's perspective there is very little to be concerned with outside of the need to fully understand how to fill the DME tank and understanding any range limitations that may differ from their diesel powered vehicles. The vehicle will look and feel the same and will likely be slightly quieter with less knocking at start up when compared to diesel.

Maintainers will have added challenges regarding the replacement of DME fuel components and fully understanding any updated troubleshooting techniques that may differ from diesel. A new breed of mechanic may need to evolve: one that can repair and overhaul engines that run on diesel, LPG, LNG, CNG, DME or combinations of any of these fuels. There will be challenges that will arise from the fact that LNG and CNG must be maintained more like a spark ignition engine whereas DME must be maintained as a diesel engine.

There are features that will distinguish DME fuel systems from conventional diesel. One of the more significant ones involves vapour fuel leaks. Currently, if a diesel vehicle sustains a fuel leak, the liquid fuel simply leaks onto the vehicle and then onto the surface below and there is no secondary effect, other than contamination to the environment. However, in a DME vehicle, a vapour based under-hood fuel leak could result in extra DME fuel being ingested into the air intake system of the vehicle, which could cause the engine to over-speed. This is similar to how vacuum leaks are detected on gasoline powered vehicles via the use of propane being expressly directed near vacuum hoses until the engine over-speeds. Mechanics and operators will have to be aware of this phenomenon, however, they are already likely aware of this if they already have experience operating and maintaining LNG and CNG engines.

Training re-fullers how to handle DME should not be markedly different than the training that is provided for those personnel who handle LPG fuels such as propane and for those of CNG. The material characteristics and handling requirements are all relatively similar.

10 CONCLUSIONS

General

Dimethyl Ether (DME) is an organic compound with the chemical formula CH_3OCH_3. For decades it has been used in a variety of products and applications such as propellants in aerosol cans, cooking fuels, solvents and medical treatments due to its lack of odour and toxicity and its ability to be absorbed into the troposphere. However, it can also be made into a viable alternative for diesel fuel, most notably for use in heavy haul transport vehicles.

The report contains much data that is interspersed throughout all of the sections. Many of these facts and figures have been presented again, in Table 23, comparing DME to diesel, natural gas and LPG in one view. In some cases, preference was given to complete and/or recent US data over dated/incomplete Canada-only data therefore some data are presented in US dollars and units.

Table 23 – Combined Properties of Various Fuels

	Fuel				
Factor	**Diesel**	**LPG**	**LNG**	**CNG**	**DME**
UN #	1202	1075	1972	1971	1033
Hazard Class	3	2	2.1	2.1	2.1
Cetane #	40 to 50	NA	<10	<10	55 to 60
RON	15-25	109	127	127	~35
Mass Heating Value	42.5 MJ/kg	46.6 MJ/kg	48.62 MJ/kg	45.71 MJ/kg	27.6 MJ/kg
Volumetric Heating Value	36.04 MJ/l	23.67 MJ/l	21.88 MJ/l	7.93 MJ/l	18.38 MJ/l
Flammability Range	0.6 to 7.5	2.1 to 10.1	4.4 to 17	4.4 to 17	3.4 to 18
Liquid Density	848 g/l	508 g/l	450 g/l	174 g/l	666 g/l
DGE	1.00	1.55	1.56	3.98	1.88
CO_2* non-DGE tailpipe	2.64 kg/l	1.52 kg/l	1.26 kg/l	0.48 kg/l	1.28 kg/l
CO_2* DGE tailpipe	2.64 kg/l	2.36 kg/l	1.96 kg/l	1.91 kg/l	2.41 kg/l
Expansion from liquid to vapour	NA	270 times volume	600 times volume	600 times volume	375 times volume

Factor	Diesel	LPG	LNG	CNG	DME
Fuel Tank Size	Small	Small-medium	Medium	Large	Small-medium
Empty Fuel Tank Weight	Light	Medium	Heavy	Heavy	Medium
Fuel Tank Cost	$	$$	$$$	$$$	$$
Typical HD Vehicle Range	1,900+ km	~1,000 km	~850 km	~600 km	~1,100 km
Spark Plugs	No	Yes	Yes	Yes	No
Cost/gal (US consumer Jan 2015)	$3.06	$4.51	$2.68	$2.35	??
In-tank Temp	Ambient	~10 °C	-162 °C	Ambient	
Tank Pressure	0 psi to 40 psi	~75 psi	5 psi to 200 psi	3,000 psi to 3,600 psi	~75 psi
Tank Position on Truck	Side mount	Side mount	Side mount	Rear rack mount	Side mount
Engine Oil	API-C	API-S	API-S	API-S	?
Auto Ignition Temp	523 K	560 K	853 K	853 K	508 K
Number of Refilling Stations in Canada	7,244	2,200	17	78	0
Vapour Density	NA	1.882 kg/m^3	0.686 kg/m^3	0.686 kg/m^3	1.993 kg/m^3
Relative Fuel Consumption	100%		105% to 120%	105% to 120%	??
Heavier than Air?	Yes/liquid	Yes	No	No	Yes

Production

Unlike conventional diesel which is produced from non-renewable crude oil, DME can be produced anywhere using renewable products like natural gas, crude oil, propane, residual oil, pulp and paper waste, agricultural by-products, municipal waste, fuel crops such as switchgrass, coal, and biomass such as forest products and animal waste. This provides a great deal of flexibility for production since facilities do not need to be located near sources of crude oil but can be setup any place where bio based feedstocks or natural gas can be found, or produced.

The current estimated yearly production of DME is approximately 5 million to 9 million tons, depending on the cited source. The literature review revealed many methods by which DME may be produced. In general though, DME is currently produced via the dehydrogenation reaction of methanol. Based on current projections, it is likely that the abundance of North American natural gas and a high level of animal waste will provide ample sources for future

DME production without reliance on offshore resources. It takes approximately 1.4 tons of Methanol to produce approximately 1.0 ton of DME. Other forms of production such as the use of pulp and paper process waste such as black liquor were also identified. A joint venture between Volvo and Chemrec in the North of Sweden produced 4.3 tons of black liquor based DME per day to power a dedicated fleet of four tractor-trailers.

Oberon Fuels manufactures skid mounted small scale DME production units meant to replace large scale infrastructure projects that could cost hundreds of thousands of dollars. The units can produce between 3,000 and 10,000 gallons of DME a day (11,340 litres to 37,800 litres. This process is ideally suited to regional haulers with large fleets who see each of their vehicles daily and want to reduce costs by not only self fueling, but self-producing the fuel.

Chemical Properties

DME exists as an invisible gaseous ether compound under atmospheric conditions (0.1 MPa and 298 K) but must be condensed to the liquid phase by pressurization above its vapour pressure at about 0.5 MPa (5.1 bar/73 psi) at 25 °C to be used as a diesel fuel alternative. One of the more significant features of DME is the lack of a direct carbon-to-carbon bond that is found in traditional diesel fuels. Conventional diesel contains no oxygen whereas DME is an oxygenated fuel and contains about 34.8% oxygen by mass with no carbon-to-carbon bonds. The increase in oxygen content can reduce the precursors to soot formation like C_2H_2, C_2H_4 and C_3H_3. The presence of oxygen can also reduce auto ignition since the C-O bond energy is lower than the C-H bond energy found in conventional diesel. DME has approximately 66% of the energy content, by mass, and about 50%, by volume, of diesel fuel.

The air/fuel ratio of DME fuel at stoichiometric conditions is approximately 9 versus 14.6 for diesel meaning that complete combustion of 1 kg DME requires less air than that of 1 kg diesel fuel. However, more than 1 kg of DME is required to provide the same amount of energy as 1 kg of diesel. DME has a much higher, and wider, flammability range (i.e. the volume of fuel, expressed as a percentage in an air mixture at standard conditions, where ignition may occur) in air than the three hydrocarbon fuels (gasoline, diesel and propane but very similar to natural gas. DME is sulfur free whereas even ultra-low sulfur diesel (ULSD) contains some sulfur.

Most #1 and #2 pump diesel fuels have cetane numbers between 40 and 45 and many bio-diesels have CN greater than 50. DME has a cetane number between 55 and 60, which makes it very suitable for a diesel cycle engine. This reduces engine knocking and engine noise when compared to engines powered with conventional diesel and also helps to provide a more complete combustion process with less wasted fuel, particularly at engine start up or when in-cylinder temperatures cool off. Fuels such as propane and natural gas have high octane numbers but cetane numbers less than 10, making them impractical for dedicated use in a diesel cycle engine unless they are combined with at least some diesel as an ignition source.

DME in the liquid state has low viscosity and low lubricity, two properties which strongly affect the maximum achievable injection pressure in a fuel injection system: viscosity allowing it to readily pass through narrow passages and the lack of lubricity can accelerate the wear of surfaces moving relative to each other such as the feed pump, the high pressure injection pump, and injector nozzles. Due to the low viscosity and lubrication characteristics, fuel additives are mandatory to improve the fuel viscosity to make DME a viable fuel for on road engines.

In addition to its low lubricity and viscosity, DME adversely affects many types of plastics and rubbers and also dissolves nearly all known elastomers found in the fuel system. Retrofitting a vehicle to burn DME that is equipped with elastomers and certain plastics could result in very short service life of those components and possible fuel leaks or a reduction in working pressure. Laboratory tests have demonstrated that DME is compatible with Teflon® and Buna-N rubber. Tests have demonstrated that the bulk modulus of DME is approximately 1/3 that of conventional diesel. Research has demonstrated that due to DME's low elastic modulus, the compressibility of DME is higher than that of diesel fuel, which means that the compression energy in the DME fuel pump is greater than that in the diesel fuel pump. The differences between diesel and DME with regards to lubricity, viscosity, bulk modulus and energy density means that many components in the fuel system must be changed when converting from diesel to DME. The fuel injection timing and duration must also be altered.

Some laboratory tests using pure DME instead of diesel have caused pump failure in less than 30 minutes. Adding a small amount of lubrication significantly increased lubricity but still not to the point where it could be considered acceptable for the typical expected life of a highway tractor. They concluded that raising the lubricity of DME to acceptable levels may not be possible but changing the designs of the pumps to accept pure DME could be a much more viable option. Some researchers have concluded that one of the more significant challenges in using DME as a diesel-fuel substitute is the modification, tuning and management of the engine fuel delivery system.

Emissions

Particulate Matter (PM), or soot formation, in a DME-fueled engine is almost zero because DME has an oxygen content of 35% and no carbon-to-carbon bonds. Many tests and research programs have demonstrated that DME powered vehicles have PM levels that are orders of magnitude less than diesel PM levels and can pass all current worldwide emissions regulations without the use of any type of diesel particulate filter or trap. Studies have shown that as much as 99% of the PM released from a DME engine is in the nano particle size, which can cause more damage to human health than the larger particle sizes. However, it is not clear from the research if the absolute volume and count of PM particles could pose a risk to human health as a result of tailpipe emissions from Canadian vehicles given that this could be 99% of what is already a miniscule value.

The relationship between NO_x formation, the use of selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) is less clear than the formation of particulate matter. The near zero levels of PM means that PM burn off in the engine is not required thus in cylinder temperatures can be lowered, which reduces the levels of NOx. Some tests have demonstrated that DME powered vehicles can be operated without the use of SCR for NOx reduction with the addition of light EGR to reduce NOx levels and diesel oxidation catalysts to reduce carbon monoxide and hydrocarbon levels to below emissions regulation levels. However, most of these tests were conducted when emissions regulations were slightly less stringent than today. More testing will be required to determine if a DME powered vehicle can pass current emissions regulations for PM, NOx, CO and HC without the use of SCR and what level of EGR and catalysing would be required to compensate for this lack of SCR. Additionally, it will be important to maintain a level of EGR that does not increase fuel consumption or contribute to engine wear. The primary benefits of removing SCR from vehicles are as follows: reducing cost, reducing weight, reducing the need to replenish a consumable fluid and removing a piece of equipment that can cause an engine derate when a fault occurs, be it actual or nuisance.

Research has shown that HC and CO emissions from a DME-fueled engine are usually lower than or equal to that of a diesel engine. However, if SCR is removed and EGR is used to cool the in cylinder temperature it will result in higher levels of CO and HC which can then require the use of a diesel oxidation catalyst to reduce CO and HC levels. Additionally, if high levels of engine injection advance are requested (more than 20 degrees) it can result in levels of CO and HC that are significantly higher than what is currently allowed in North America for on-road and off-road vehicles. Therefore, careful consideration must be given to the inter relationship between engine timing and EGR levels otherwise the reductions of PM may be offset by increase in other pollutants.

DME produces less exhaust, by mass, than diesel and less CO_2 than diesel. DME produces more water than diesel but not orders of magnitude more (as is the case with fuel cells) therefore it is assumed that the incremental effect to cold road surfaces would be minimal, when compared to diesel. For every 43 MJ of fuel energy, DME produces approximately 0.70 kg less total exhaust, 0.30 kg less CO_2, and 0.55 kg more H_2O than diesel fuel. This may not be a large reduction in CO_2 but it does mean that an engine that is slightly above the maximum allowable levels for CO_2 under Canada's new GHG reduction strategy could potentially pass the regulations if fueled with DME, assuming horsepower and fuel consumption remained the same.

The Carbonyl compounds such as formaldehyde (HCHO), acetaldehyde (CH_3CHO), and formic acid (HCOOH) have all been found to be higher for DME than for diesel. This is due to the high Oxygen content and additives in DME whereas diesel is Oxygen-free. Formaldehyde can be reduced to negligible levels by the use of a diesel oxidation catalyst whereas catalysts have no effect on the reduction of acetaldehyde. Careful attention will need to be paid to the lubricity additives that are mixed with DME as they can adversely affect the generation of these Oxygen based compounds and the reduction in PM could be offset by an increase in other toxins.

It is clear that any DME powered vehicle can pass any emission standard in the world (at the time of report preparation) for PM without the use of a particulate filter or trap.

Comparisons to other Alternative Fuels

DME's energy density (1.88 DGE) on a volumetric basis is lower than that of LNG (1.56 DGE) but higher than that of CNG (3.98 DGE). Other alternative fuels such as CNG, LNG and LPG are all used in spark ignition engines and therefore require special maintenance such as spark plug replacement. DME powered engines can be maintained similarly to diesel engines with more attention being paid to fuel lubricity to prevent premature failure of pumping and fuel injection components.

DME is stored at pressures that are higher than diesel, but similar to LPG and much lower than CNG.

CNG and LNG fuel tanks are significantly heavier and more expensive than DME fuel tanks. Some papers indicate that LNG and DME tanks can be more than 350 kg heavier than similarly sized DME tanks. Exact figures were difficult to obtain but the size and weight of DME fuel tanks should only be marginally higher than diesel fuel tanks, however, range will be reduced due to the lower energy content of DME.

Because DME has approximately only two thirds of the energy content of diesel by mass, and 50% by volume and only 80% of the physical density, the fuel consumption data must be multiplied by the diesel gallon equivalency (DGE). Typical DME raw test results are between 2.5 mpg and 3.0 mpg at cruising speed. However, when DGEs are considered, the values correspond to fuel consumption rates of over 5.00 mpg which is consistent with current heavy duty tractor fuel consumption values.

DME can be stored for long periods of time in outdoor storage tanks that are exposed to direct solar radiation without any boil off or venting.

Vehicle Modifications

As a minimum, DME powered vehicles will require a new fuel tank, new fuel lines, new fuel pumps and injectors as well as new/improved seals and gaskets and modified engine management mapping and software to control the timing of the fuel injections. The addition of a larger and heavier pressure vessel fuel tank (similar to LPG) and some form of EGR could possibly be offset by the removal of the diesel particulate filter and possibly the SCR componentry. Whereas LNG and CNG vehicles must carry very heavy pressure vessel tanks that can reduce payload capacity, the net effect on weight to a heavy duty vehicle powered by DME should be negligible when compared to current diesel powered vehicles. If SCR can be removed there will likely be a small weight savings for DME. However, the range of the vehicles will be reduced to approximately 50% of current distances, which could necessitate a much larger tank which would then increase the weight to current diesel truck levels.

Many other minor vehicle modifications must be implemented such as pressure relief valves, non sparking metal components such as brass, shields and valve covers etc. However, none of these components will add enough weight to seriously affect the payload capacity of a load carrying vehicle.

Maintainability and Reliability

Unlike most LNG/CNG/LPG engines that require spark plug replacement at specified intervals, DME engines can be serviced in a similar fashion as other compression ignition engines. Despite the fact that many components on DME engines must be changed from conventional diesel engines, they are still the same type of components so the maintenance philosophy can remain.

The low lubricity of DME could necessitate, at least in the near term, an increase in fuel component inspections and or replacement. More data will be required to determine the long term effects on the reliability of all fuel wetted components for long haul operations where fuel pump failure far away from the maintenance base would be considered a highly undesirable situation.

Approximately 7% less air, and presumably 7% less dirt and contaminants, will be drawn into a DME engine compared to diesel engines. It is not likely that air cleaner/filter intervals will need to be modified based on this relatively small change in air flow. Nonetheless, DME engines should be slightly cleaner than diesel engines under identical situations.

Diesel engines currently require oils that are specifically formulated to manage the soot that is generated inside the combustion chamber. More study will be required to determine if the lack of soot in DME powered engines could, or should, result in the use of a different grade of oil, perhaps more similar to those used in gasoline engines.

Vapour fuel leaks under the hood can cause engine overspeeding as raw fuel is ingested into the air intake system.

More study would be required to better understand how DME would affect the mean time between failure of any fuel wetted component, including the fuel system and the engine itself.

Safety and Protective Equipment

In general, DME behaves like propane/LPG and can be handled as such. As with LPG, DME is heavier than air and can pool on the floors of underground garages thus preventing an explosion hazard if a source of ignition were to be dropped into the pool.

Fire fighters will be required to receive training on the ways to extinguish a DME fed fire since improper technique can lead to explosions.

DME is considered a dangerous good in the hazard class 2.1 and must be transported in a vehicle with a placard mounted that contains the necessary information.

The MSDS sheets for DME indicate that personnel who handle the product should wear gloves and eye protection as well foot protection. The level of protection is similar to personnel who are dispensing LPG and CNG and slightly less than those dispensing LNG.

From the driver's perspective there is very little to be concerned with outside of the need to fully understand how to fill the DME tank and understanding any range limitations that may differ from their diesel powered vehicles so that they are not stranded in inclement weather. The vehicle will look and feel the same and will likely be slightly quieter with less knocking at start up when compared to diesel.

Cold Weather Operations

Very little data could be found related to the performance of DME in cold weather climates such as Canada. The joint Volvo and Chemrec DME project was a two year project that operated continuously throughout all of Sweden's four seasons, including their cold winter months. Some of the operations were conducted as far north as the 65th parallel which runs through all three Canadian territories. The test team did not report any operational issues related to ice, snow or cold temperatures. It is not known if Sweden uses salt on their roads to the same extent that is used in some Canadian provinces. Some specific recommendations for cold weather operations were found involving the use of corrosion resistant tanks and fasteners to minimize the risks of salt induced corrosion perforation. However, these recommendations are likely already 'best practices' for diesel vehicles. Rigorous yearly inspections may be required to ensure that fuel tank integrity has not been compromised due to corrosion. DME tanks are pressure vessels and are therefore more rugged than conventional diesel tanks thus the risk of tank failure is actually lower. However, the consequences of a tank failure are potentially more severe since it is a pressurized gas that could be expelled at high velocity whereas diesel fuel remains, at all times, in the liquid unpressurized phase.

Fuel Availability and Cost

At the time of report preparation there were no known DME fuel stations in Canada. This is in contrast to the approximately 100 public and private LNG and CNG stations found across Canada and the abundance of diesel fuel stations. This lack of publicly available DME means that the use of DME in heavy vehicles will likely have to be staged if is to be accepted by the industry. The first phase of DME use would most certainly be for use in fleets that return back to their base every evening for refuelling, be they public or private. These could include urban transit buses, waste collection vehicles, vocational vehicles such as concrete mixers etc. The current lack of infrastructure would make it nearly impossible for long haul tractor trailer operations or for intercity motor coach buses. The reduced range of DME vehicles combined with the fact that, once converted, DME vehicles can no longer operate on any other fuel will dictate that a significant DME network must be constructed along major corridors to support fleet operators who choose to commit to using DME.

The consumer cost of a litre of DME is extremely difficult to quantify at this time. The International DME Association states that the consumer cost of DME is roughly 75% to 90% that of LPG. They also noted that pure LPG prices fluctuate more since LPG is a petroleum based fuel and must follow global petroleum pricing. Oberon, the largest producer of DME in the

United States simply states that DME is “competitive with diesel prices” but does not list a consumer cost on their website

Until more accurate data are available, it is fair to assume that the cost per km of delivered DME, on a diesel gallon equivalency, is approximately the same as diesel fuel. The cost per litre may be lower, but since more DME must be burned per distance driven, the cost per km of the fuel should be similar. However, it must be restated that not enough data were available to perform such a calculation with any certainty.

11 ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
API	American Petroleum Institute
ASHRAE	American Society of Refrigeration and Air Conditioning Engineering
AST	Automotive and Surface Transportation
ASTM	American Society for Testing Materials
Bhp	Brake Horsepower
CFD	Computational Fluid Dynamics
CFR	Cooperative Fuel Research
CGA	Canadian Gas Association
CN	Cetane Number
CNG	Compressed Natural Gas
CNGVA	Canadian Natural Gas Vehicle Alliance
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSA	Canadian Standards Association
CST	Centistokes
DEF	Diesel Exhaust Fluid
DGE	Diesel Gallon Equivalent
DME	Dimethyl Ether
DOC	Diesel Oxydation Catalyst
DPF	Diesel Particulate Filter
ECM	Electronic Control Module
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
eTV	ecoTechnology for Vehicles
FDIS	Final Draft International Standard
g	grams
GAW	Gross Axle Weight
GHG	Greenhouse Gas Emissions
GVW	Gross Vehicle Weight
HC	Hydrocarbon

HHDDT	Heavy Heavy-Duty Diesel Truck (cycle)
HHV	Higher Heating Value
hp	Horsepower
Hr	Hour
IDA	International DME Association
ISO	International Standards Association
K	Kelvin
km	Kilometer
km/h	Kilometre per Hour
kWh	Kilowatt Hour
L	Litre
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
M	Metre
MBTA	Massachusetts and Bay Area Transit Association
MJ	Mega Joule
mph	Miles per Hour
MSDS	Material Safety Data Sheet
NMOG	Non Methane Organic Group
NO_x	Oxides of Nitrogen
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NTSEL	National Traffic Safety and Environment Laboratory
OEM	Original Equipment Manufacturer
Pa	Pascal
PM	Particulate Matter
PTFE	Polytetrafluoroethylene
RON	Research Octane Number
s	Second
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
THC	Total Hydrocarbons
ULSD	Ultra Low Sulfur Diesel

UN	United Nations
USA	United States of America

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The following references formed part of the literature review but were not specifically cited in this document due to redundancy with other references. Nonetheless, they were all useful in some way towards the generation of this document : [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104] and [105].